



**Escola Tècnica Superior d'Enginyeries
Industrial i Aeronàutica de Terrassa**

UNIVERSITAT POLITÈCNICA DE CATALUNYA

END OF BACHELOR DEGREE PROJECT (EBDP)

LABS MATERIAL FOR ACTIVE LEARNING IN A COURSE OF PHOTONICS

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Degree in Industrial Electronics and Automation

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1. INTRODUCTION

This study is focused on the subject “Photonics. Optics Applied to Engineering” which is provided in the Degrees of Engineering of the ESEIAAT. The required resources to carry out the practice sessions are limited, causing that students cannot do the same practice in the same session. Therefore, students are divided into 5 groups and each group performs a different practice. Often students can not complete activities during the two-hour class. I intend to develop practical teaching resources based on active learning methods with the goal of improving the academic performance of students.

1.1. Aim of this EBDP

This work is aimed at getting students to be more self-sufficient at the laboratory during these five practical sessions. As a result of this, performing all the operations of any of the five practices must take students less than two hours. After leaving the laboratory, they also have to be able to analyse the data acquired in order to get accurate results which have to be explained in a report. Finally, it is also the objective of this work to design an individual evaluation system.

1.2. Scope of this EBDP

Taking the practices developed during last school year as a reference, the main obstacles that prevent students from finishing all the activities on time are: difficulties understanding the English language, wrong identification of the material needed and incorrect application of the procedures.

Regarding the drafting of the report after the laboratory session, the calculations sometimes are complex. And related to the evaluation system, all members of the same group get the same mark, which is some occasions could create disagreements.

The didactic material to be designed has to solve these drawbacks, thus reducing the queue time when students need to ask a question to the teacher during a practical session, making the calculations of the report easier and ensuring an individual evaluation.

By attending personally some practical sessions, it will be checked that these teaching resources can work as expected.

1.3. Requirements of this EBDP

This teaching material has the following requirements:

- It has to be delivered on 19th May 2017.
- It has a budget of 100€.
- It must ensure that all the operations of any of the five practices can be carried out in less than two hours.
- It must adapt to the available area in the laboratory.
- It must be flexible in order to facilitate future changes.
- It must allow students to use it during the practical sessions at the laboratory.
- It must ensure eye protection against laser beams.

- It must be able to be installed and uninstalled quickly because the laboratory is a shared resource.
- It must take into account that there are 4 students per practice.

1.4. Justification of the usefulness of this EBDP

This teaching material is important because it will improve the following items:

- Reduction of the queue time, making the sessions less stressful for the teacher.
- Increase in students' satisfaction because they will feel more guided and will be able to take the most of these practices. Writing the report will also be easier and students will be able to be assessed also individually.
- Decrease in the queue time of the teacher who has to use the laboratory just after a Photonics session. His students will also thank you that they will have more available area.

2. State of the art and possible solutions

Since the teaching material to be develop will be made most of videos, I reproduce an interesting article written by the University of Queensland that describes how this tool can improve students' performance:

There are many benefits to using video in education as shown in several decades of research. Salman Khan in 'Let's use video to reinvent education' (20 mins) describes the transformative way video can impact on teaching and learning and encourages teachers to consider the flipped classroom model where learners can digest lecture content at their pace and explore content more deeply during class time.

See The Art of Educational videos by Macquarie University for the breadth of approaches to making effective videos.

Facilitating thinking and problem solving

Shepard and Cooper (1982) and Mayer and Gallini (1990) made the connection between visual clues, the memory process, and the recall of new knowledge. Allam (2006) observes that the creative challenge of using moving images and sound to communicate a topic indeed engaging and insightful, but adds that it also enables students to acquire a range of transferable skills in addition to filmmaking itself. These include research skills, collaborative working, problem solving, technology, and organisational skills. (Bijnens, N.D.)

Assisting with mastery learning

In some cases, video can be as good as an instructor in communicating facts or demonstrating procedures to assist in mastery learning where a student can view complex clinical or mechanical procedures as many times as they need to. Furthermore, the interactive features of modern web-based media players can be used to promote 'active viewing' approaches with students (Galbraith, 2004).

Inspiring and engaging students

More recently, Willmot et al (2012) show that there is strong evidence that digital video reporting can inspire and engage students when incorporated into student-centred learning activities through:

increased student motivation

enhanced learning experience

higher marks

development potential for deeper learning of the subject development potential for deeper learning of the subject development potential for deeper learning of the subject

development of learner autonomy

enhanced team working and communication skills

a source of evidence relating to skills for interviews

learning resources for future cohorts to use

opportunities for staff development (CPD). (p.3)

Authentic learning opportunities

The work of Kearney and colleagues show the benefits of using video to produce authentic learning opportunities for students (Kearney and Campbell 2010; Kearney and Schuck, 2006), and how 'ivideos' encourage academic rigour from an advocacy, research based perspective.

Approach to possible solutions

The different alternatives to solve the problems described are the following:

- Two teachers instead of just one during the lab sessions.
- Reduction of the number of activities of each practice.
- Reduction of the number of practices.
- Distribution of the same activities into 6 practices instead of 5.
- Increase in the number of hours for carrying out these practices.
- Decrease in the number of students per practice.
- Developing a course based on a Moodle platform with teaching resources like videos, links, templates...
- Redesign of the physical resources.

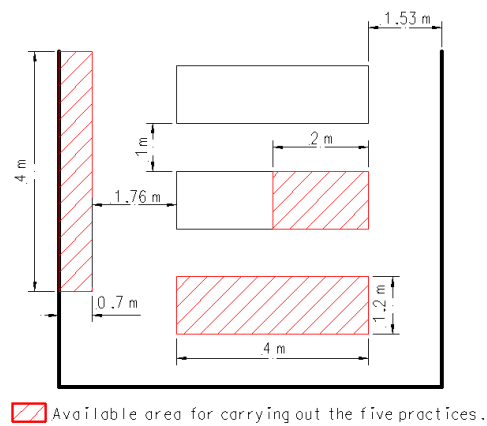
There are two types of solutions that are going to be applied: on the one hand there is the solution to the physical problems related to the laboratory material necessary to

carry out the 5 practices and on the other hand there is the solution of digital type that has to do with the elaboration of didactic material on a Moodle course.

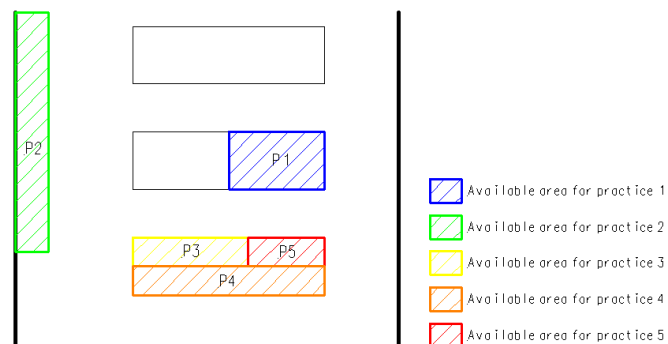
3. Physical solution

3.1. Distribution of practices in the laboratory.

This laboratory is a shared resource and therefore not all workbenches are available. The following plan shows the workbenches available for performing photonic practices.

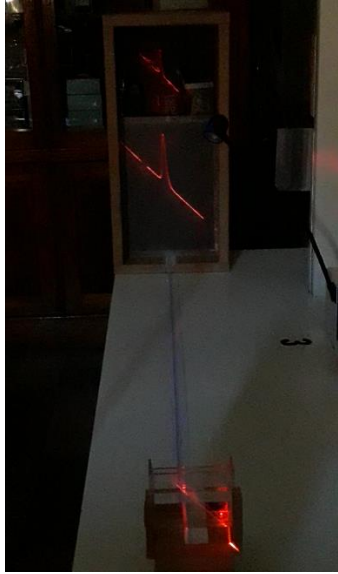


The following drawing shows how the five practices in the laboratory are distributed.

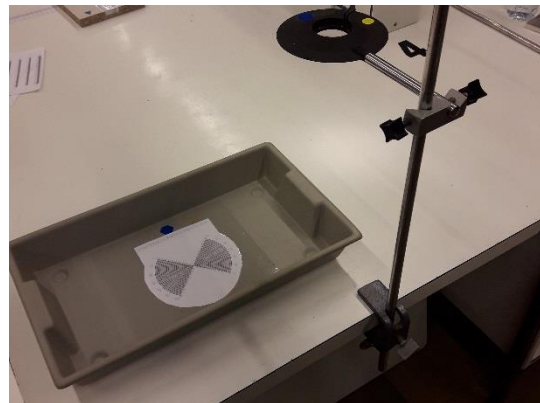


Some installations of the practices are shown below:

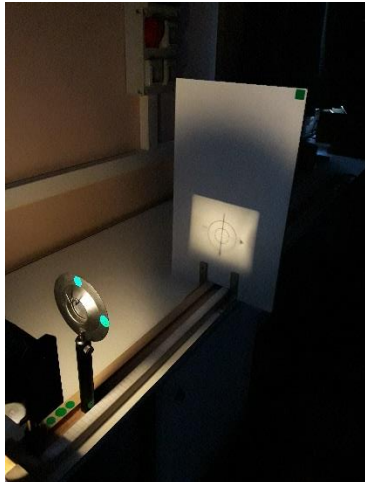
INSTALLATION OF PRACTICE 1A



INSTALLATION OF PRACTICE 1D



INSTALLATION OF PRACTICE 2B



INSTALLATION OF PRACTICE 3B



INSTALLATION OF PRACTICE 4B


























INSTALLATION OF PRACTICE 5A



3.2. Labelling of the material

The labelling of the material needed in each practice with stickers with different colors and geometric shapes will avoid confusions. The following table shows the criterion followed to label the material required for each practice and section. For example, the material needed to carry out the activities belonging to the section C of the practice 3 have a yellow pentagon.

	PRACTICE 1	PRACTICE 2	PRACTICE 3	PRACTICE 4	PRACTICE 5
SECTION A					
SECTION B					
SECTION C					
SECTION D					
SECTION E					
SECTION F					
SECTION G					

3.3. Ease of installation

Regarding the physical mountings, the substitution of metallic supports by wooden ones will facilitate the installation and uninstallation of the practices. The following picture shows the material needed in the section A of the first practice and the second one illustrates how fast its installation is.



Additionally, the following two pictures shows how the installation of practice 1C is simpler thanks to the replacement of the metal supports by wooden devices.



The following photos show the contrast between the installation of the practices of the previous year with respect to the current course.

PRACTICE 1 BEFORE



PRACTICE 1 AFTER



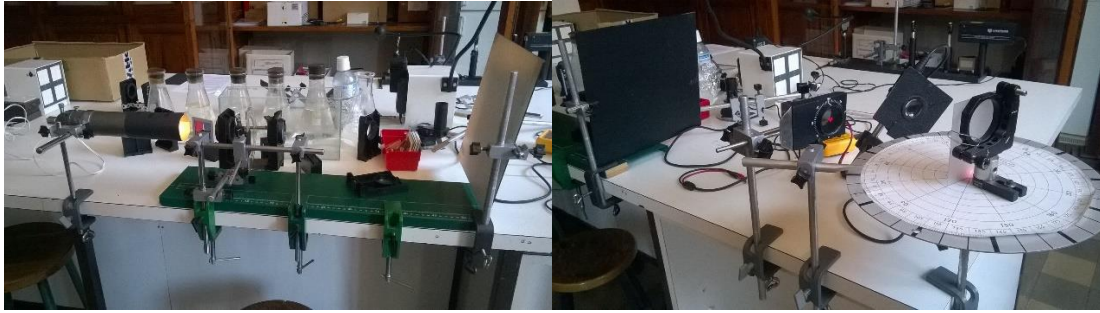
PRACTICE 2 BEFORE



PRACTICE 2 AFTER



PRACTICE 3 BEFORE



PRACTICE 3 AFTER



PRACTICE 4 BEFORE



PRACTICE 4 AFTER



PRACTICE 5 BEFORE



PRACTICE 5 AFTER

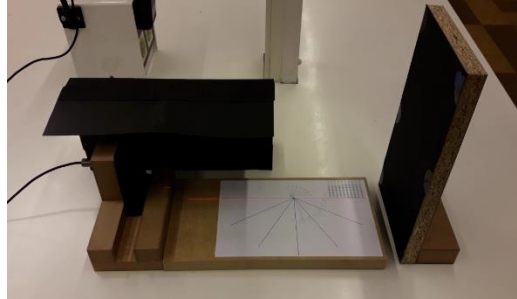


3.4. Use of new technologies

In particular, it is about replacing the operations of drawing by hand by taking photos. This has been achieved with the design of screens with millimeter vegetable paper. Three screens have been made: one for practice 1, one for practice 4 and one for practice 3 (the latter without a grid).

3.5. Eye protection against laser beams.

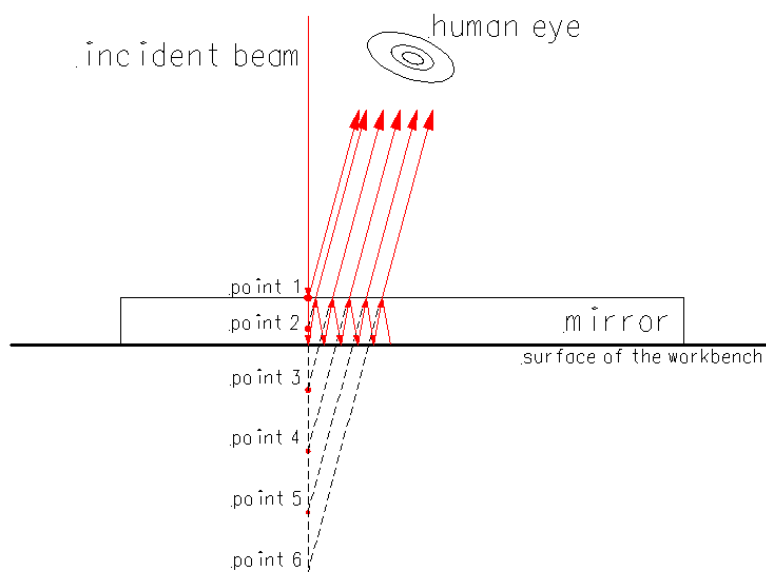
A total of seven plates covered with black cardboard have been made. It is important to use them in practices 1A, 1C, 3B, 4A, 4B and 4D. In the following photograph it can be seen how the use of these eye protection plates prevent the laser beam from colliding with the eyes of a student who is performing the index of refraction in practice 1C.



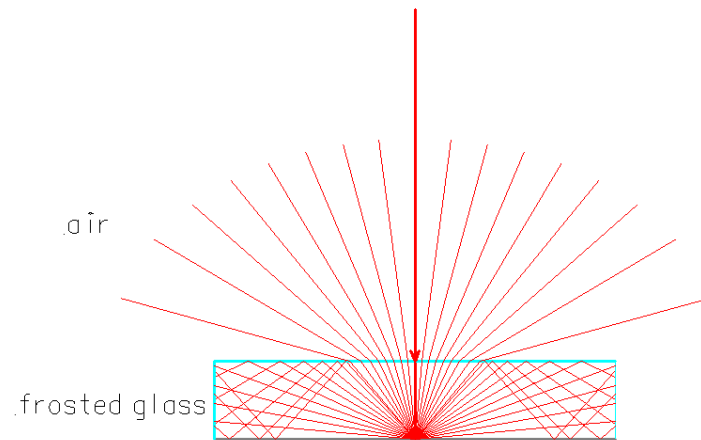
3.6. Drawings

The drawings are classified into two groups: those that facilitate the understanding of physical concepts and those that improve the measurement of physical variables. The first ones are related to the Pffund effect, reflection and refraction in plano-parallel plates. They are shown below:

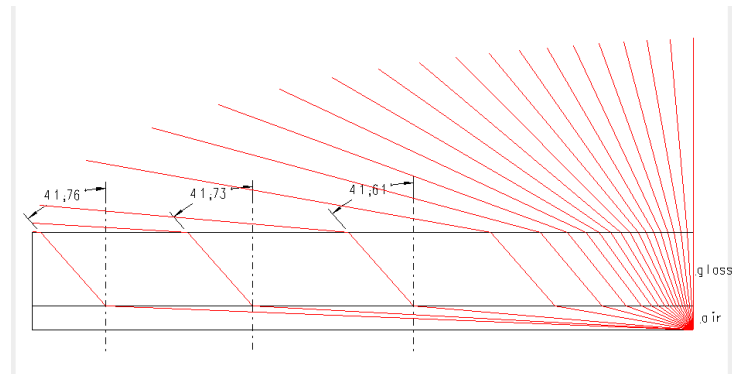
Drawing 1: specular reflection.



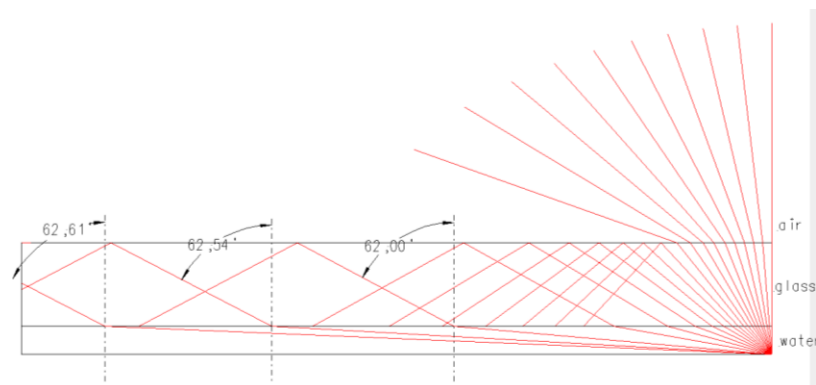
Drawing 2: diffuse reflection in a frosted glass



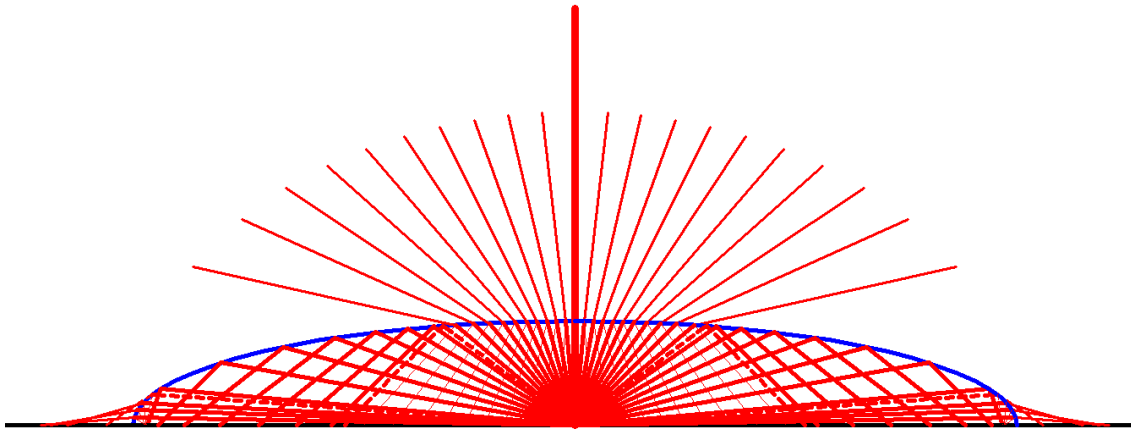
Drawing 3: diffuse reflection in a transparent glass with air underneath



Drawing 4: diffuse reflection in a transparent glass with water underneath

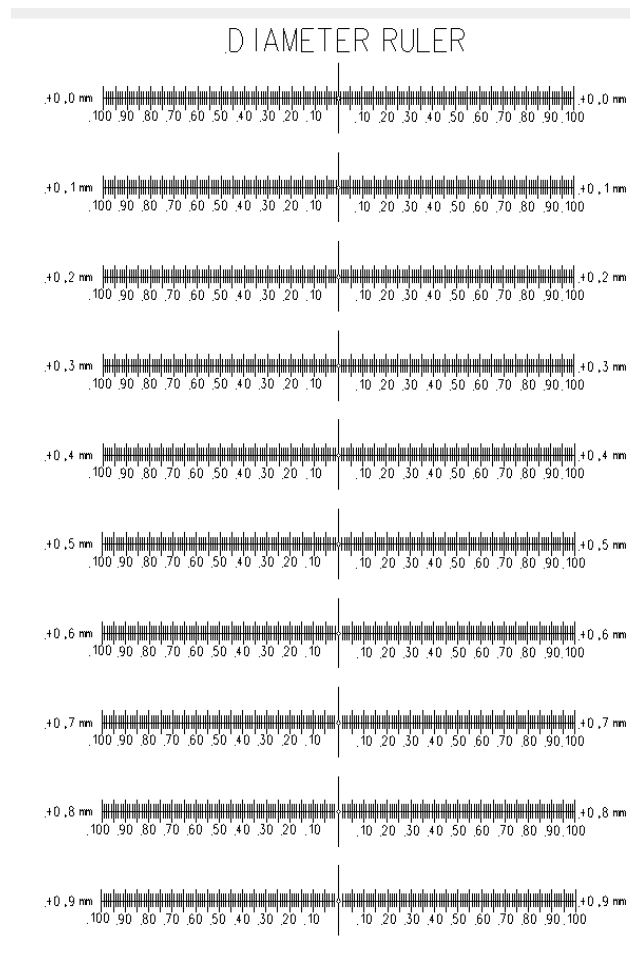


Drawing 5: lighting of the edges of a water droplet



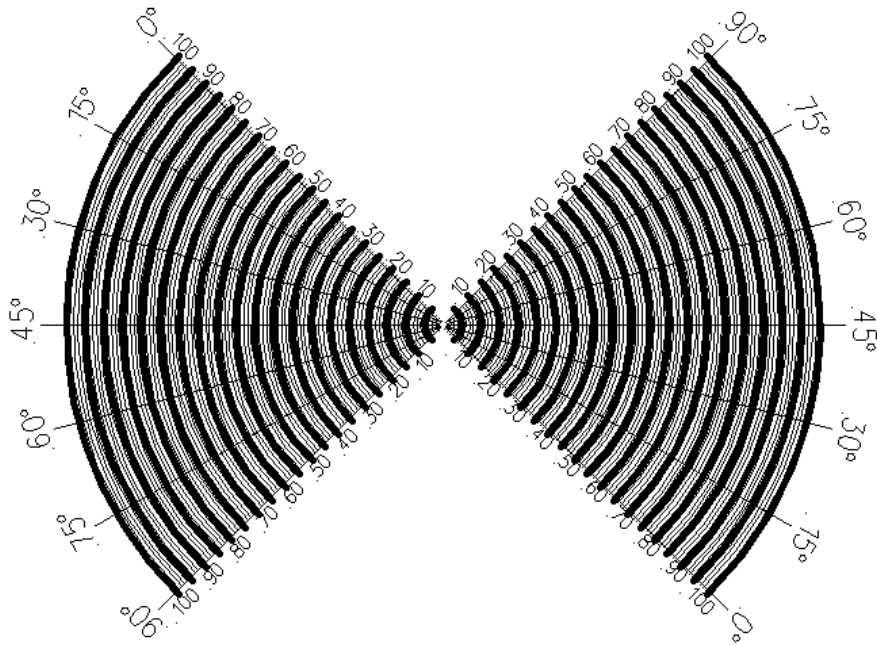
The drawings that improve the measurements are the following ones:

Drawing 6: diameter ruler with an accuracy of tenths of mm

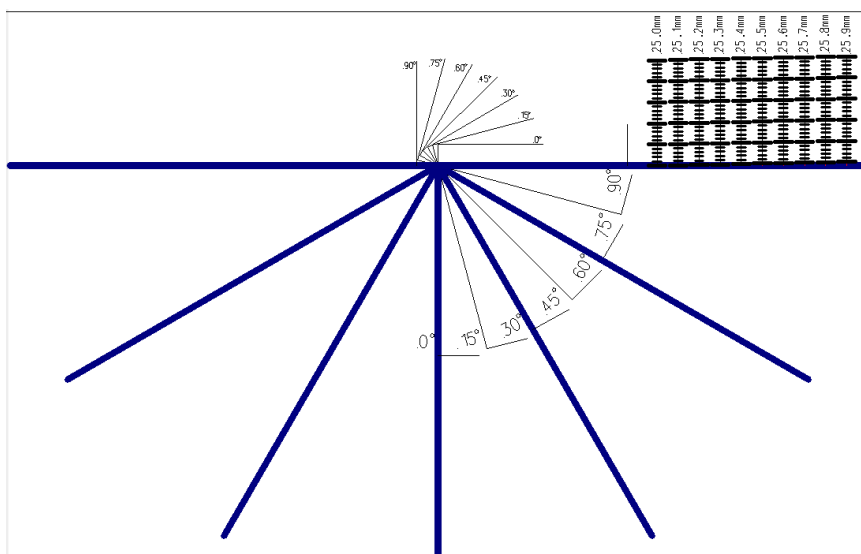


Drawing 7: diameter ruler with an accuracy of mm

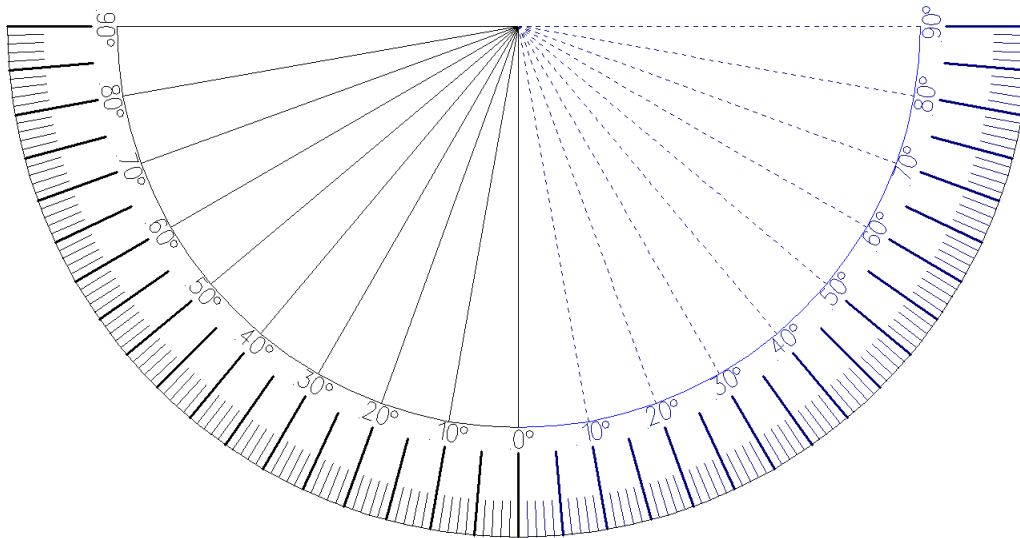
DIAMETER RULER EXPRESSED IN mm



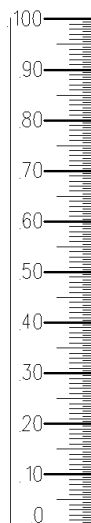
Drawing 8: template for measuring the index of refraction



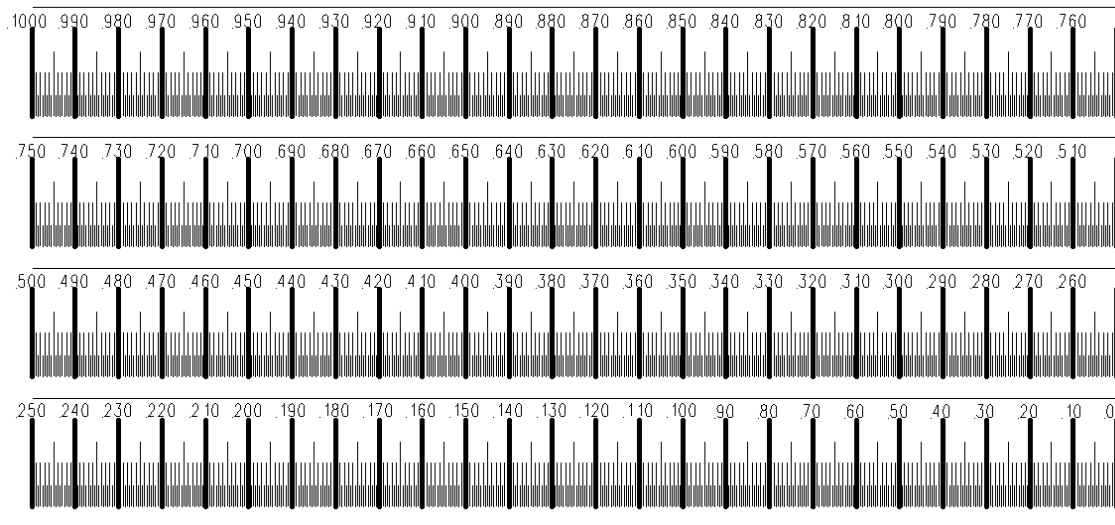
Drawing 9: template for measuring the angle of incidence



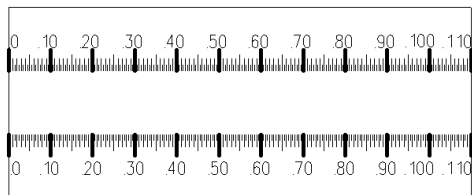
Drawing 10: ruler for measuring the depth of the vessel



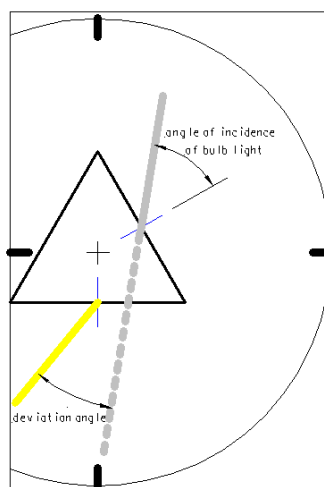
Drawing 11: ruler for measuring distances



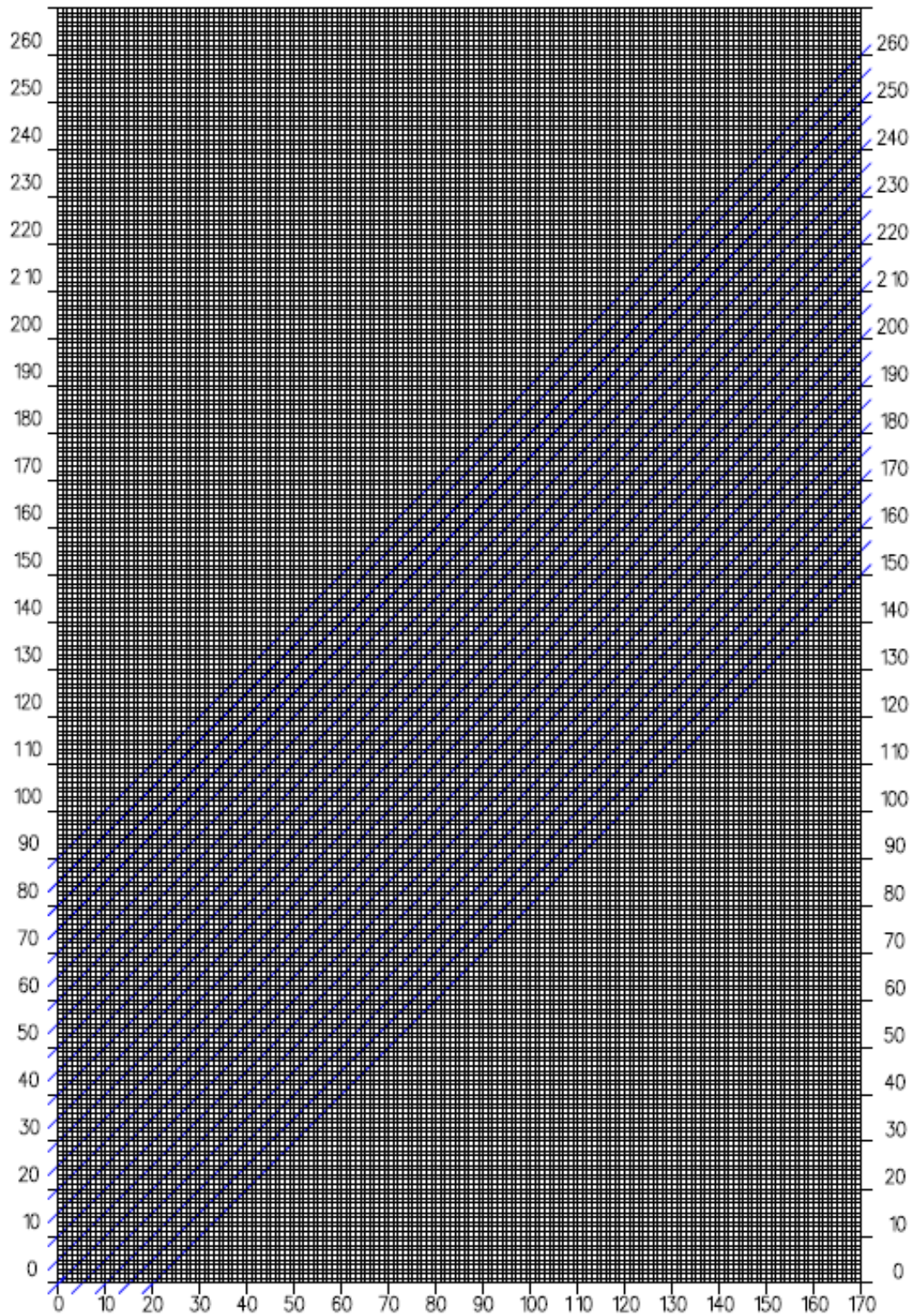
Drawing 12: ruler for measuring interferences fringes



Drawing 13: platform for placing the prism on the spectrometer



Drawing 14: grid for measuring areas



4. Digital solution

The digital solution has to do with the development of documentation based on videos, text files, spreadsheets, links to applets, and evaluation questionnaires. All this documentation is organized in a Moodle course.

There are two main reasons that explains why a course based on a Moodle platform is going to be created. First, the use of mobile phones and laptops connected to internet via Wi-Fi are generalized amongst students and secondly the UPC has a virtual learning environment called Atenea which uses Moodle as a technological base.

The following picture shows the appearance of this Moodle course.



4.1. Assessment of the level of English

This teaching material is entirely written in English and is mainly intended for Catalan-speaking students. Therefore it is advisable to know their level of English to anticipate in advance the possible difficulties they may have to understand the instructions.

Their level of English has been assessed through a 30-question questionnaire. It has been done taking as reference the test of English level of the Vaughan group and adapting it to a laboratory environment of photonics.

The following picture shows some examples of questions and the annex 4 contains the 30 ones.

3. In connection with this picture, which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ The one that's here is the Abbe Refractometer.
- ☐ The one here is an Abbe Refractometer.
- ☐ That what is here is an Abbe Refractometer.

QUESTION 3



4. One student says that it is 13.2 mm in diameter and his teacher replies:

Marca solo un óvalo.

- ☐ You have right.
- ☐ You're right.
- ☐ You're wrong.

QUESTION 4

5. Which sentence is grammatically correct?

Marca solo un óvalo.

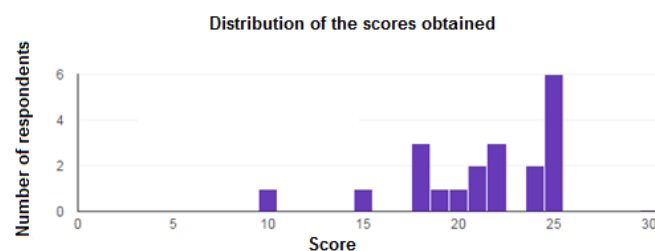
- ☐ Listen your teacher if you want to pass this subject.
- ☐ Listen to your teacher if you want to pass this subject.
- ☐ You listen to your teacher if you want to pass this subject.

The results were as follows:

20 students out of 39 took the English test obtaining the following results:

- Basic level: 2 students
- Intermediate level: 18 students
- Advanced level: 0 students

The following graph shows the distribution of the scores obtained:



These results allow me to affirm that only 46% of the students demonstrate to have an adequate knowledge of English. The configuration of the members of the groups of practices must take into account that at least there must be one student with an adequate level of English per team.

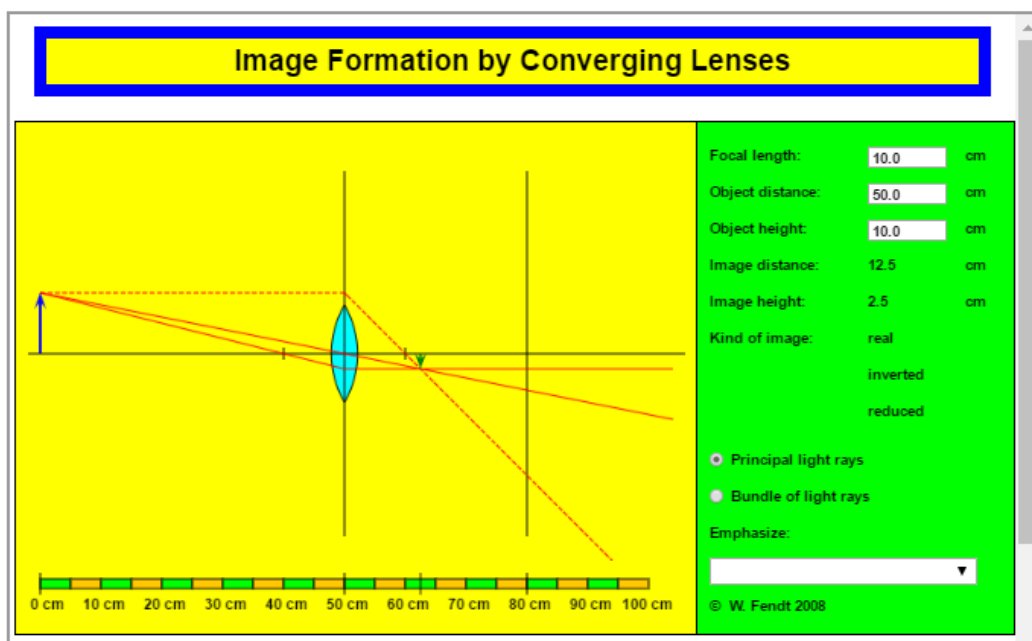
4.2. Applets

The use of applets significantly improves the learning of theoretical concepts that must be put into practice in a laboratory.

We have a link to 12 applets made by the University of Barcelona and 4 other links with applets made by Walter Fendt.

This picture shows an example of Applet which help to understand image formation by lenses:

Applet about Image Formation by Converging Lenses



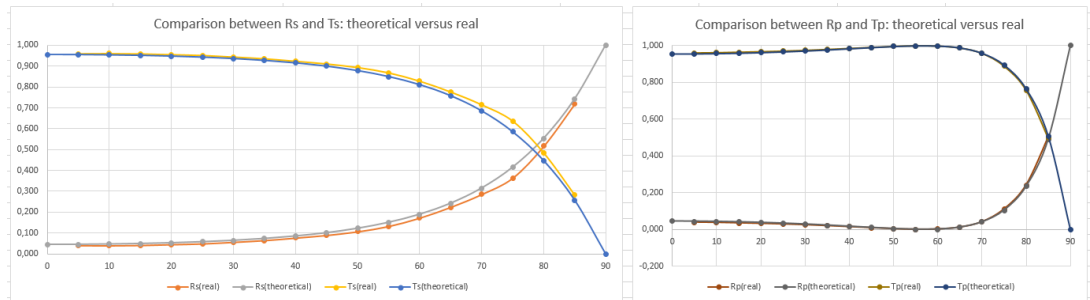
4.3. Scripts of the practices

There are a total of 5 text documents which describe each practice in detail. These documents are based on the practices carried out in previous courses and they have been adapted to the innovations introduced. They are reproduced in annex 1.

4.4. Spreadsheet files

The templates made with spreadsheets are intended to make the calculation of the results easier. There are five spreadsheet templates for the following practices and sections: practice 1 section A, practice 3 section A, practice 3 section B, practice 3 section E and practice 5 section A.

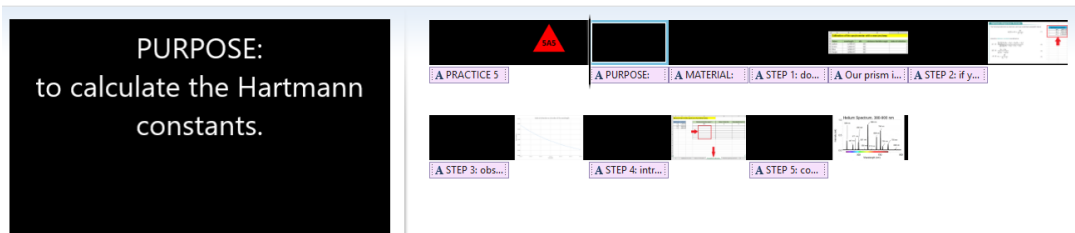
The following picture shows how easy it is to compare the theoretical results about the transmittance and reflectance of a piece of glass with the experimental ones:



4.5. Videos

These videos facilitate the identification of material and give examples to understand the procedure to be followed. There are a total of 47. Each section has at least one video. They can be used to prepare the practical session and also during and after it. They have been made with the Windows Movie Maker video editing program.

The following pictures shows an example of an edition. There are five more examples in annex 3.



4.6. Group evaluation

The evaluation of the members of a team is done through the delivery of a report for each practice. In the Moodle platform, five tasks are enabled to allow students to post their reports.

4.7. Individual evaluation

A questionnaire has been designed with 23 questions related to each of the sections in which the practices have been divided. These 23 questions are randomly chosen out of 42 available. This ensures that each student will answer different questions. The annex 2 contains an example of a questionnaire.

5. SUMMARY RESULTS

Improvements have been observed with regard to the autonomy of the students to carry out the practices without the constant intervention of the teacher.

This has been observed during 7 practical sessions. During the last session in which all the videos were already available, there was an increase in the autonomy of the students. The tasks of the teacher relied mainly on supervising that the practices were being carried out correctly. There were no difficulties in identifying the right material and with some exceptions, the groups were able to complete the activities of each practice. As a consequence of all this, there were no students queueing for the teacher to be attended.

I can conclude that the objectives of this work have been fulfilled.

6. Summary budget

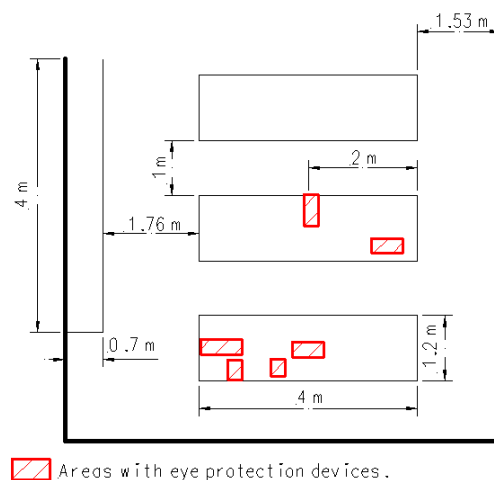
The completion of this Moodle course plus the updating of the laboratory material amounts to 8170 euros. The breakdown of expenses is specified in the following table.

Carpentry work	
3 screens	€ 60,00
One turning platform	€ 50,00
One optical bench	€ 30,00
7 eye protection plates	€ 30,00
Moodle course design	
47 videos	€ 4.700,00
5 spreadsheet templates	€ 1.000,00
English level test	€ 500,00
Photonics questionnaire	€ 300,00
Moodle course design	€ 500,00
Update of practice scripts	€ 1.000,00
TOTAL	€ 8.170,00

7. Analysis and assessment of environmental implications

The realization of these practices of photonics does not generate any type of environmental problem. Disposing the mixture of alcohol and water in the sewerage system does not have any harmful effect for the environment since the amount of alcohol is only 10 ml and also it is also diluted in water.

In contrast, it is important to mention in this section the emphasis put on eye protection against laser beams. The following plan indicates the areas where eye protection devices are required. These places correspond to the sites where practices 1A, 1C, 3B, 4A, 4B and 4D are carried out.



8. Conclusions and recommendations of continuity

The three objectives have been fulfilled: there is an increase in the autonomy of the students that results in a reduction of the queue when they need to consult the teacher, the analysis of the results is easier and there is an individual evaluation system.

Regarding the requirements, it is verified that most of them are fulfilled except that in some cases some students have not been able to complete all the activities of a practice in less than two hours. In these cases, it is often agreed that students have a low level of English and also a low interest in the subject.

Connecting with recommendations of continuity, a logistic study would more accurately assure the ability to carry out the activities of any of the five practices in less than two hours. In particular, the next phase to complete this work consists of a detailed study of all the operations that students should carry out in each one of the practices.

Some improvements can be achieved by applying the following management techniques:

- Physical distribution of resources.
- Discrete event model to simulate how students are using resources during laboratory sessions and also to study how their academic performance can increase by using new technologies based on digital educational platforms.
- Queuing theory to reduce the wait times.
- PERT techniques to plan and programme all activities.

9. Bibliography

<http://www.ub.edu/javaoptics/>

https://www.youtube.com/playlist?list=PLX2gX-ftPVXWA5TjEhVQSQQzZ-5_5Nui8

Notes of the subject of "Photonics. Optics applied to engineering"

http://www.abc.es/sociedad/20150418/abci-test-nivel-ingles-vaughan-201504172150_1.html

https://www.ted.com/talks/salman_khan_let_s_use_video_to_reinvent_education

<http://www.uq.edu.au/teach/flipped-classroom/index.html>

<http://teche.ltc.mq.edu.au/art-educational-videos/>

Allam, C. (2006) in Bijmens, M., Vanbuel, M., Verstegen, S., Young C., [Handbook on Digital Video and Audio in Education](#), Creating and using audio and video material for educational purposes, The Videoaktiv Project.

[The Dial-e framework Digital Artefacts for Learner Engagement](#) was developed to support the pedagogically effective use of a range of digital content.

'Grassroots Video' is a chapter in the 2008 edition of [The Horizon Report](#) and covers the explosion of publically created video content on the Internet.

[Video Use and Higher Education: Options for the Future](#) is a 2009 report of the study of the use of video in twenty higher education institutions in America.

In this Educause article, [Video: The Good the Bad and the Ugly](#) Willis (2009) questions ad hoc use of video in education and how it should be used within emerging modes of scholarly production.

10. Annex 1: scripts of the five practices

Practice 1: Refractive Index measurement. Light propagation in homogeneous and nonhomogeneous media.

In this experiment, we study the light propagation in uniform and non-uniform media. We use the light deviation in propagation through a nonhomogeneous medium for measuring liquid concentrations, their spatial distribution and time evolution. We also use the straight light propagation to measure the refractive index of liquids and thickness of flat layers.



SECTION A: Light propagation in a nonhomogeneous media

Material

- He-Ne laser, $\sim 1\text{mW}$
- Cylindrical lens.
- A transparent container with flat walls.
- A small piece of polyester that can float and a syringe.
- Two miscible liquids, the refractive index of which must differ in ~ 0.02 .
- Screen with graph paper on it.
- Independent supports for laser, lens and container.

Introduction

Light does not propagate straight in a medium that presents a refraction index gradient but tends to bend to higher index regions. For instance, a light beam with normal incidence on a medium layer showing a refractive index that increase in vertical direction will bend vertically and it will present an angular deviation behind the layer. The refractive index of each spatial point can be deduced from the light deviation. Further, one can get information about the cause that produces the refractive index gradient. In this experiment, we create an index gradient using two liquids with different refractive index, water and alcohol. The measurement of the refractive index distribution allows deducing the alcohol concentration in height.

Method

Place the two miscible liquids inside the transparent narrow container. First, fill the container with water up to 40mm. The second liquid (10ml of alcohol) should be located over the water with a clear interface between the two liquids. We can use a plastic film or a floating polyester piece and the syringe to avoid the mixture. Water has a smaller refractive index than the solution, creating the gradient. Alcohol concentration will gradually diffuse varying in time the index gradient. The cylindrical lens is intended to open the laser beam to obtain a light plane at 45° that illuminate the front face of the container in a diagonal line. The distance between the cylindrical lens and container **b** should be large enough to consider a perpendicular incidence of light rays in the container, each one with a different height, see fig. 1.

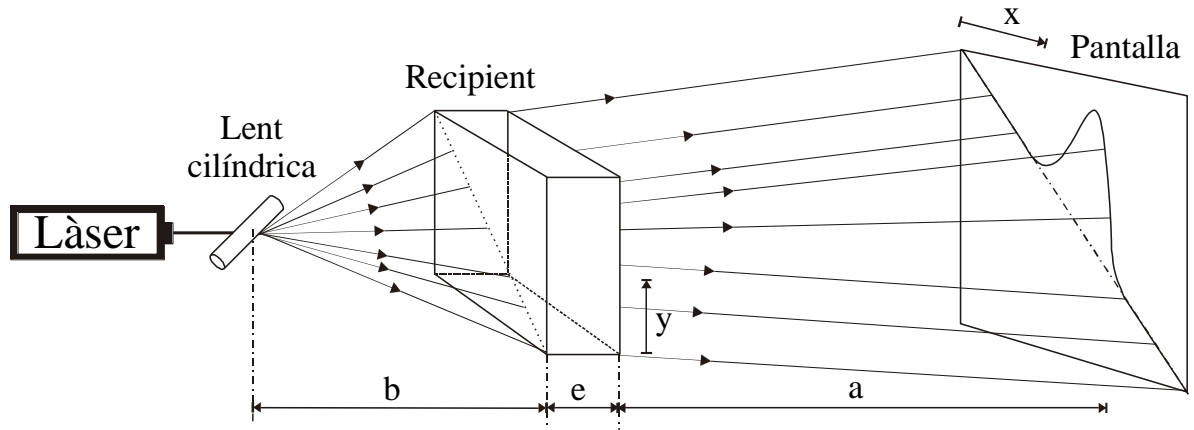
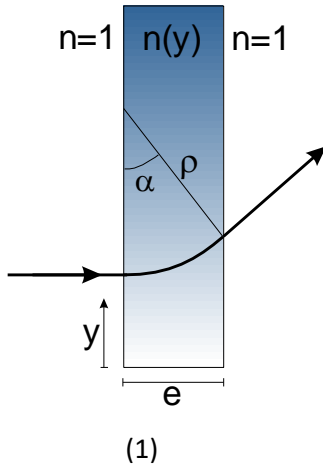
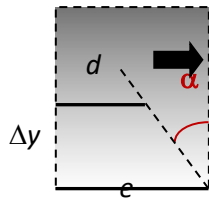


Figure 1: experimental device consisting of a laser, a cylindrical lens that expands the beam, a container that contains two immiscible liquids with different refractive index, and a screen where the laser beam is projected. The distance from the lens to the container is b , the width of the container is " e " and " a " is the distance between the screen and the container.



The vertical ray deviation can be calculated considering two rays whose height differ in Δy and crossing the container at positions with refractive index n and $n + \Delta n$. Due to the different refractive index, the two beams cross different distances (e and d in the figure) and thus, the wavefront suffers a deviation with an angle α :

$$\tan \alpha \approx \alpha \approx (e - d) / \Delta y \approx \left(e - \frac{en}{(n + \Delta n)} \right) / \Delta y \approx \frac{e \Delta n}{n \Delta y}$$



$$\alpha = \frac{e \, dn}{n \, dy} \quad (2)$$

Therefore, the light rays describe curved trajectories and the total deviation angle α depends on the refractive index vertical variation. For a homogeneous medium, far from the gradient zone the beam suffers no deviation. An additional deviation must be considered due to the refraction in liquid-air interface and evaluated with the Snell law:

$$\sin \alpha \approx \alpha; \sin \alpha_2 \approx \alpha_2 \Rightarrow n \alpha = n_{\text{aire}} \alpha_2 \Rightarrow \alpha_2 = e \frac{dn}{dy} \quad (3)$$

On the screen, the ray shift $\delta(y)$ for a large enough screen distance a , $a \gg \delta(y)$ is:

$$\delta(y) = atg\alpha_2 \approx a\alpha_2 = ae \frac{dn}{dy} \quad (4)$$

thus, the vertical shift in screen $\delta(y)$ depends on the known distances a and e and the derivative dn/dy .

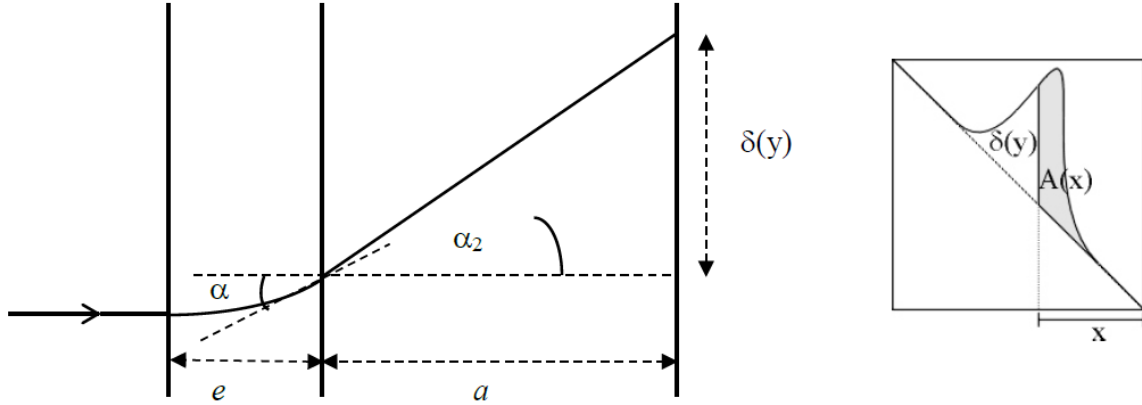


Figure 3. Deviation of a ray of light through the container containing a medium with a refractive index that varies with the height y .

The 45° tilted light plane and distances directly relates the x position with a vertical position in the container that can be deduced by geometry from fig.1 and fig.3:

$$x = \frac{a+b}{b} y \quad (5)$$

where b is the lens-container distance, a is the screen-container distance and e is the container thickness that is considered to be small: $b \gg e$. Combining equations 4 i 5 we get:

$$\delta(y) = ae \frac{dn}{dx} \frac{dx}{dy} = \frac{a(a+b)e}{b} \frac{dn}{dx} \quad (6)$$

To obtain the index value at each vertical position y , $n(y)$, we can integrate dn/dy :

$$n(y) = n(0) + \frac{b}{a(a+b)e} \int_0^x \delta(x) dx = n_1 + \frac{b}{a(a+b)e} A(x) \quad (7)$$

where n_1 is the index at $y=0$ (water index), $A(x)$ is the area given by the curve at a certain position x in the screen (shaded area in fig.3).

Measuring distances a , b and e and drawing the light curve on the screen, it is possible to measure the area $A(x)$ and obtain the refraction index at any y value using eq.(7).

The diffusion of alcohol in water decreases the index gradient in the two liquids interface along time. Although, it can be proved that the total area, A_{Total} , is constant in time. A_{Total} can be calculated just taking a large enough x value where the corresponding refractive index $n(x)$ is the one of the upper liquid, n_2 (alcohol-water mixture):

$$n_2 - n_1 = \frac{b}{a(a+b)e} A_{Total} = Constant \quad (8)$$

This result can be seen drawing the curve that appears on the screen for several different moments and measuring the respective total areas. The refractive index of the upper liquid n_2 can be calculated from eq.(8). Keep in mind that the refraction index depends on wavelength, thus we are measuring the refractive index at the laser wavelength (He-Ne laser $\lambda=6328\text{\AA}$).

Measurement of the liquid concentration

The relative concentration of the two liquids at each height $c(y)$ is related with the refractive index $n(y)$. This relationship is linear for the considered liquids and thus, we can easily calculate the concentration as:

$$c(y) = \frac{n(y) - n_1}{n_2 - n_1} \quad (9)$$

where $c(y)$ is the relative concentration of the upper liquid. For $n(y)=n_1$, then $c(y)=0$ that corresponds to 0% of the upper liquid (100% of water) and for $n(y)=n_2$, $c(y)=1$ corresponding to 100% of the upper liquid (alcohol-water mixture).

Procedure (video) (template1A1)

1. Check that the laser beam is in horizontal direction.
2. Locate the container with facets perpendicular to the laser beam. Distances a and b must be large compared to recipient thickness. For instance: $a \approx 1200$ mm and $b \approx 600$ mm. Measure the recipient thickness e .
3. Place the recipient in front of the diagonal light plane like fig.1.
4. Fill half of the container with water (refractive index: $n_1=1,334\pm0,001$).
5. Introduce a plastic film or polyester piece floating on water. Use a syringe to fill the recipient with the second liquid dropping it on the plastic film or small polyester piece in order to create a separated layer with the second liquid (alcohol-water mixture).
6. Place the screen.
7. Take 4 pictures. The first one at minute 0, the second one at minute 20, the third one at minute 40 and the last one at minute 60. Meanwhile, do other activities of sections B, C and D.
8. Measure the total area, A_{Total} , for the 4 curves and verify that it keeps constant. Calculate the corresponding refractive index of the second liquid n_2 using eq.(8).
9. Use the spreadsheet template and plot the relative concentration $c(y)$ of each curve in a graph. Plot the temporal evolution of the alcohol concentration at each spatial point.

Additional experiments:

Do the following experiences while waiting the 20 minutes between measurements.

1B

SECTION B: Measurement of the refractive index with an Abbe refractometer

Material

- An Abbe refractometer
- Water
- Alcohol

Introduction

The Abbe refractometer is used to measure the refractive index of liquids. It is based on the limit angle (or critical angle) between the liquid and a glass with high refractive index.

Procedure (video)

1. Measure the refractive index of water and water-alcohol mixture that you are using in section A. Open the refractometer, drop a drop of liquid on the glass and close it. Illuminate the refractometer from the rear part. Looking through the eyepiece there is a line between darkness and light, which corresponds to the limit angle. Match the limit angle line with the cross turning the set screw and directly read the liquid refractive index through the second eyepiece.

1C

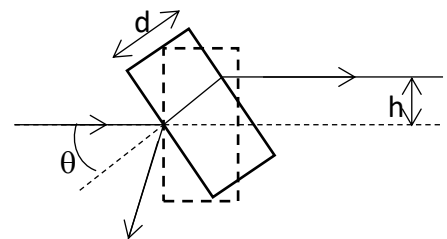
SECTION C: Measurement of the refractive index of a plane-parallel plate.

Procedure (video)

Using a laser in horizontal direction and a cylindrical lens generate a vertical light plane. Place a white paper on the table and the plane-parallel plate on it. Orientate the plane-parallel plate perpendicular to the beam and draw a line on the position of the front face and rear face. Draw the reflected and the transmitted (refracted) beam path. You can use the template for measuring

1. Turn the plate and draw the reflected and the transmitted beam path for 5 different incident angles θ . The refracted beam is always parallel to the incident one but shifted a distance h depending on the incident angle θ , plate thickness d and refractive index n fulfilling the expression:

$$n = \frac{\sin \theta \sqrt{d^2 + h^2} - 2hd \sin \theta}{d \sin \theta - h}$$



2. Calculate n as the average of the 4 measurements

1D

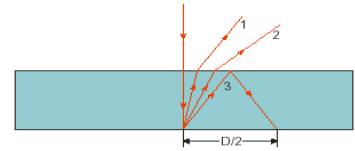
SECTION D: Pffund effect. Reflection and refraction in plane-parallel plates

Explain what you observe in the following situations:

1. (Video) Illuminate a single point on the table by focusing a laser beam and explain why you can see the bright point on the table but you cannot see the laser beam through the air.
2. (Video) Place a mirror on the table focusing the laser beam on the mirror. How many bright points can you see through the mirror? Explain the observation of these

points.

3. ([Video](#)) Focalize the beam on a frosted glass from the polished face. A darker area appears around the central point. The same pattern is observed illuminating the beam in spilled water on the table. Explain this darker circular zone around the central bright point. Why the water droplet edges are illuminated?
4. ([Video](#)) Wipe the table. Focalize the beam on a transparent plane-parallel glass of thickness h on the table. Explain why there is a brighter circular area around the central point (Pfund effect). Repeat it for glass plates with different thickness. Explain your observations.
5. ([Video](#)) Measure the bright diameter D for different thickness h . Measure each thickness h with the calliper (peu de rei).
6. ([Video](#)) Prove the relationship $D = \frac{4}{\sqrt{n^2 - 1}} h$ and calculate n .
7. ([Video](#)) Repeat point 4 but dropping a bit of water on the table and place the transparent plane-parallel glass on it. Explain the formation of the dark circle and the brighter ring.
8. ([Video](#)) Repeat point 5.
9. ([Video](#)) Repeat point 6.
10. ([Video](#)) Fill a tray with some water and measure how deep this layer is by means of the Pfund effect.



Practice 2: Image formation and construction of classic instruments: microscopes and telescopes.

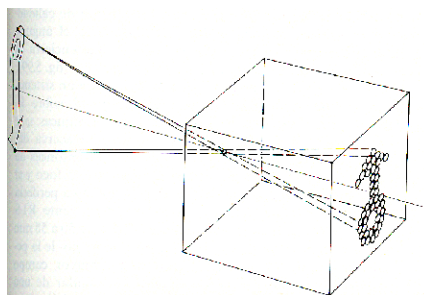
In this experiment students become familiar with lenses and with various classical optical instruments. The main features are analysed and optical systems are built with simple lens combinations.

2A

SECTION A: The camera obscura

A lens creates an image onto a screen because it is an astigmatic optical system, thus any light beam coming from an object point reaches the same point on the screen. Moreover, we can form images on a screen without any lens. A small enough hole is also an astigmatic system. In this case there is a single light beam coming from each object point, passing through the hole and reaching the screen. The diameter of the hole will determine the sharpness of the image created. A too large diameter mixes light from different points, so diameter should be small enough. Although, a too small diameter increases light diffraction that also muddies the picture.

Figure 0. The camera obscura is an opening and a screen.



1. ([Video](#)) Look at a distant illuminated object by the camera obscura. Explain how the image is formed.
2. If you are myopic, look at a distant and illuminated object in a dark environment directly and through a little hole (1-2mm). Give an explanation for the observed image sharpening.

2B

SECTION B: Measuring the focal length of a lens

Material

- Converging lenses with focals +50 and +100 mm.
- Diverging lens -100mm
- Illuminated object.
- Optical bench with ruler.
- Screen.

Focal length of converging lenses

The focal point F of a lens is the point on axis that has its image at infinity (rays from the focal point F are parallel beyond the lens). The focal point F' is the image of an axial point at infinity (parallel rays from infinity converge in F'). f and f' are the position of F and F' with respect to the lens. For thin lenses, $f' = -f$.

1. ([Video](#)) Choose a distant object, create its image on a screen (a piece of paper) using lenses of +50 and +100mm and measure the distance between lens and image (f') with a ruler. (if laboratory lights are already off you can go to the corridor).

This method to obtain f' is not very precise because the object is never at infinity. Following, we use a more precise method:

The object position s and image position s' with respect to the lens (axis origin) are related by the lens focal distance f' by the equation:

$$-\frac{1}{s} + \frac{1}{s'} = \frac{1}{f'} = -\frac{1}{f} \quad (2)$$

For $f' > 0$ (converging lens) the image focal point is at the right side of the lens. (Fig.1):

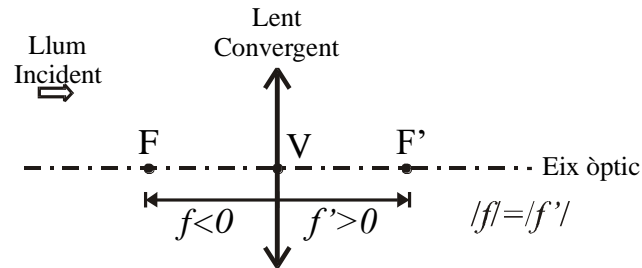


Figure 1. Schematic representation of a thin converging lens.

For $f' < 0$ (diverging lens) the image focal point is at the left side of the lens. (Fig.2):

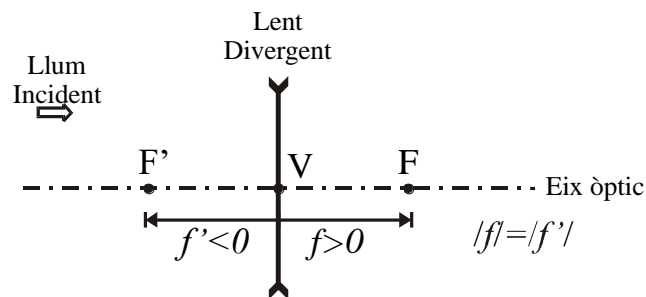


Figure 2. Schematic representation of a thin diverging lens.

The image formation can be evaluated by using the graphical method, tracing the rays through the optical system. We will use 3 rays:

- An incident ray parallel to axis reach the lens and is deviated to the image focal F' .
- An incident ray passing through the object focal point F reach the lens and becomes parallel to the optical axis
- A ray passing through the central point of the lens, i.e. the axial point of the lens, does not deviate.

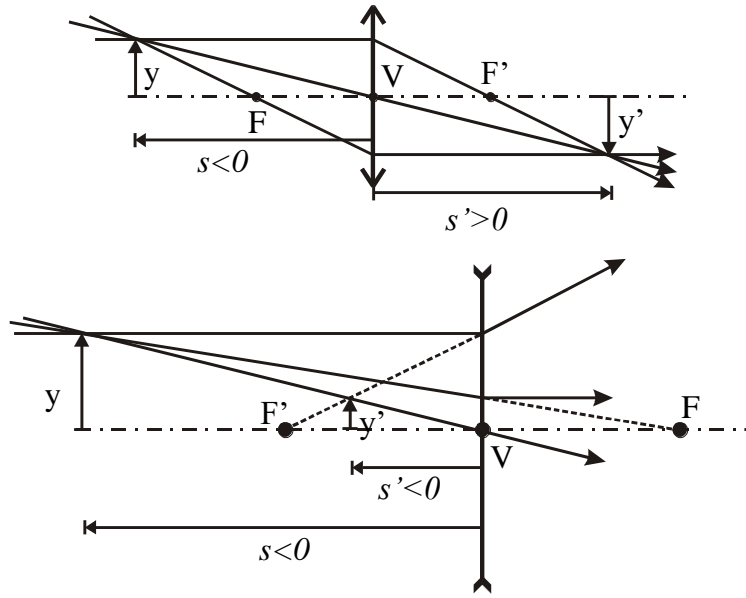


Figure 3. Graphical calculation of the formation of images by tracing rays of a converging lens (top scheme) and a diverging lens (lower scheme).

Given an object and a screen separated a fix distance L , with $L > 4f'$, the focal length of the lens to be characterized, there exist two different lens positions that creates a sharp image on the screen. This is easily demonstrated having in mind that light rays are reversible. Considering an object and its image on the screen ($L = -s_1 + s_1'$) also exist an object position $s_2 = -s_1'$ with image at $s_2' = -s_1$ that also fulfils $L = -s_2 + s_2'$. See fig. 4.

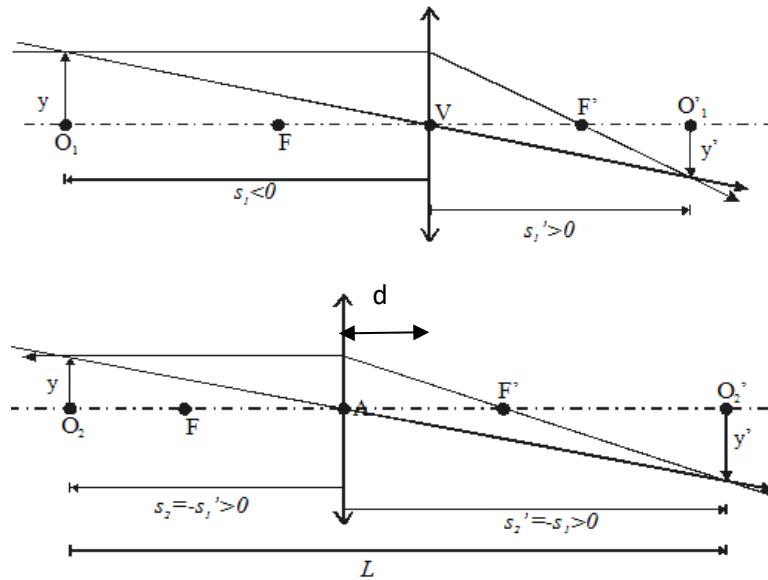


Figure 4. Representation of the two positions of the lens where the distance $L = -s_1 + s_1' = -s_2 + s_2'$ between the object point and image point are equal.

The focal length f' can be calculated from L and the distance between both lens positions d ($d=s_1'-s_2'=s_1-s_2$) using eq.(2) and taking into account that $s_2=-s_1'$:

$$\frac{1}{f'} = -\frac{1}{s_1} + \frac{1}{s_1'} = -\left(\frac{1}{s_1} + \frac{1}{s_2}\right) = -\left(\frac{s_1 + s_2}{s_1 \cdot s_2}\right) \quad (3)$$

and

$$f' = \frac{s_1 s_2}{-(s_1 + s_2)} = \frac{4s_1 s_2}{-4(s_1 + s_2)} = \frac{(s_1^2 + s_2^2 + 2s_1 s_2) - (s_1^2 + s_2^2 - 2s_1 s_2)}{-4(s_1 + s_2)} = \frac{(s_1 + s_2)^2 - (s_1 - s_2)^2}{-4(s_1 + s_2)} \quad (4)$$

Finally, using $L=-s_1+s_1'=-s_1+s_2$ and $d=s_1-s_2$, the equation can be written as:

$$f' = \frac{L^2 - d^2}{4L} \quad (5)$$

2. [\(Video\)](#) Place the screen at a distance L from the illuminated object. Move the lens along the bench up to find two lens positions with sharp images on the screen. Remember that L should be larger than $4f'$. Measure L and d , the distance between both positions and calculate f' using eq.(5) for the two lenses (+50 and +100mm).

Focal length of diverging lenses

Since a diverging lens (one with a negative focal length) always produces a virtual image, we can't measure its focal length directly. We need a converging lens to create a real image that becomes the virtual object of the diverging lens located at s_1 . The diverging lens creates a final real image at s_1' (Fig.5).

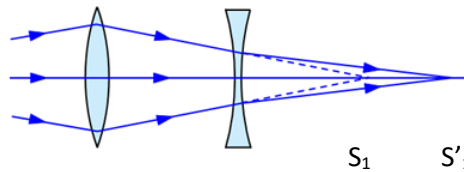


Figure 5. Assembly for measuring negative focal lengths

3. [\(Video\)](#) Using a +50mm converging lens create an image of the illuminated object on the screen. Locate the diverging lens -100 mm between the converging lens and the screen. Measure distance s_1 between the diverging lens and screen. Shift the screen up to obtain a sharp image and measure distance s_1' between the diverging lens and screen.

SECTION C: The human eye

Material

- your eyes

Description of the eye

When we study an optical instrument, we must keep in mind that the human eye is one of the optical parts of this system since the final image is created in the eye retina. Thus, a complete study must include the eye.

Light enters through pupil, an adjustable diaphragm. Light is focused by the cornea and crystalline lens creating the image on the retina. The image is sharpened by changing the crystalline radius through the action of ciliary muscles. Focusing on a distant object, the muscles relax and the eye reaches its maximum focal length that is about 2,5cm, the distance between crystalline lens and retina. Focusing near objects the eye muscles tighten, increasing the crystalline curvature and reducing the focal length. For objects closer to the “near point” your eye cannot more focus the image on the retina and it becomes blurred. The “near point” distance varies with the age from about 7 cm at the age of 10 years to 200 cm for a 60 years old person. The “near point” distance for a healthy person is considered of 25cm.

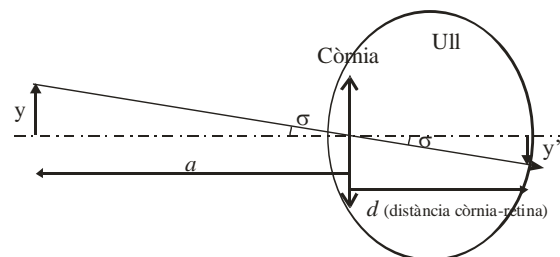


Figure 5. Image formation in the eye

The apparent size of objects is determined by their size on the retina, directly related with the incident angle σ and distance d between crystalline lens and retina (image) (see Fig. 5):

$$y' = \operatorname{tg} \sigma = d \frac{y}{a} \quad (6)$$

The smallest angular distance that can be distinguished is called *resolving power*. The resolving power of a human eye is about $5 \cdot 10^{-4}$ radians. Considering a constant distance d the apparent size is completely determined by σ , angle from axis. The *resolution* of the human eye is the smallest detail that can be distinguished. Locating the object at the near point, it corresponds to a distance of $125\mu\text{m}$:

$$\Delta y_{\min} = d_{\text{méspropera}} \cdot \operatorname{tg} \sigma_{\min} = 25\text{cm} \cdot 5 \cdot 10^{-4} = 125\mu\text{m} \quad (7)$$

Can we see an object as close as 1 cm without any lens? yes, just transform your eye to a camera obscura !! You can artificially reduce the aperture stop of the eye by placing a pinhole in front of and close to your eye. This should allow you to clearly see objects 3 or 4 cm from the pinhole!

1. ([video](#)) Look at an illuminated object on the table reducing distance up to see it blurred. Measure your near point with a ruler. Compare the lab partners' near point and explain differences.
2. ([video](#)) Look at an illuminated object on the table at 3cm directly with your eye and through a pinhole (for instance, a small hole made with a needle in an aluminium foil).

Explain the differences you noticed.

Iris

The eye adapts to low and high light levels by varying the diameter of the iris aperture. Its diameter is 8 mm when the eye is dark adapted, and may be as small as 2 or 3 mm diameter in bright light.

One limitation on resolution is the size of the pupil. The edges of the pupil produce a diffraction pattern around point images. The *Rayleigh criterion* says that two such images near each other will be resolved only when their angular separation is larger than $1.22\lambda/D$ where λ is the wavelength of light and D is the diameter of the circular aperture stop.

3. Calculate the eye resolving power using the Rayleigh criterion in dark and in bright light.

Inverted image in retina

You have often heard that the retinal image is inverted. Use a brightly illuminated pinhole held about 5cm from the eye.

4. Hold a pin head (agulla de cap) between the pinhole and the eye. The pin is less than a focal length from the eye, so it cannot form a real image on the retina. It casts a shadow on the retina, which looks reversed. Hold the pinhole 1cm to your eye. Close your eyelid, but not completely. You will see an upside down image of your eyelashes. Explain your observations.

The blind Spot

The point at the back of the eyeball where the optic nerve bundle enters is deficient in light receptors, both rods and cones, and therefore is a blind spot surrounded by the retina. It is displaced about 3mm from the optic axis.

5. ([Video](#)) Convince yourself. Close your right eye. Look at the following picture at a distance about 20cm with your left eye staring the cross. Find the distance where the circle disappears. Explain your observation.



The magnification Γ' , is the ratio between the apparent size with and without magnifying glass, i.e. the ratio between incident angles to the eye. The largest apparent size for the naked eye is obtained locating the object at a distance $d_{near point}$ ($d_{més propera}$). The eye cannot create a sharp image for smaller distances. Assuming, for simplicity, that the object O is close to the focal point F (working conditions for a magnifying glass) the magnifying power is:

$$\Gamma' = \frac{t g \sigma'}{t g \sigma} = \frac{t g \sigma'}{y / d_{més propera}} = \frac{y / -f}{y / d_{més propera}} = \frac{d_{més propera}}{f'} \approx \frac{25cm}{f'} \quad (8)$$

1. (Video) Place the +100mm lens at a distance slightly smaller than the focal length from the illuminated object. Observe the illuminated object without and with the magnifying glass. Estimate the magnification that you are observing.
2. Calculate the magnification with equation (8).
3. Vary the distance object-lens and describe your observation. Describe image magnification and image inversion increasing the distance enough.

2E

SECTION E: Compound microscope

Material

- Converging lenses of +100 mm and +50 mm.
- Optical bench.
- Illuminated object.

A Compound microscope uses an *objective lens* close to the object that creates a real and magnified image of the object inside the microscope. That image is further magnified by a second lens or group of lenses, called the eyepiece that gives the viewer an enlarged inverted virtual image of the object. The eyepiece acts like a magnifying glass to observe the intermediate image formed by the objective. It is positioned so that its focal plane is in the intermediate image plane creating a final image at infinity.

The use of a compound objective/eyepiece combination allows for much higher magnification, reduced chromatic aberration and allows exchangeable objective lenses to adjust the magnification. A compound microscope also enables more advanced illumination setups, such as phase contrast.

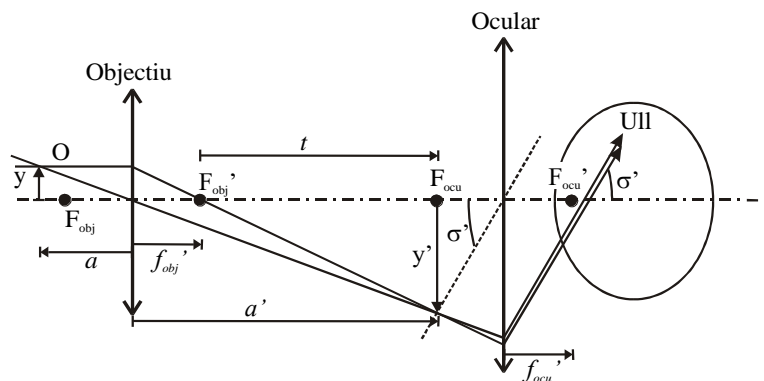


Figure 7. Image formation with a microscope

The distance between the focal point of the objective lens and the focal point of the eyepiece is called tube length t , always about 160 mm .

The magnifying power or lateral magnification is the product of the magnifications of the objective lens and eyepiece:

$$\Gamma' = \frac{y'/f'_{ocu}}{y/d_{\text{més propera}}} = \frac{y' d_{\text{més propera}}}{y f'_{ocu}} = \beta'_{obj} \cdot \Gamma'_{ocu} \quad (9)$$

The magnifying power of the objective lens:

$$\frac{y'}{y} = \frac{a'}{a} \text{ and } \frac{1}{a'} - \frac{1}{a} = \frac{1}{f'_{obj}} \Rightarrow \frac{y'}{y} = \frac{a'}{a} = 1 - \frac{a'}{f'_{obj}} = \frac{f'_{obj} - a'}{f'_{obj}} = \frac{-t}{f'_{obj}} \quad (10)$$

and thus the total magnification is:

$$\Gamma' = \beta'_{obj} \cdot \Gamma'_{ocu} = \frac{-t}{f'_{obj}} \frac{d_{\text{més propera}}}{f'_{ocu}} \approx \frac{-t}{f'_{obj}} \frac{25\text{cm}}{f'_{ocu}} \quad (11)$$

Note that the microscope magnification is negative because the image is inverted, which is any drawback in the observation of microscopic objects. The maximum magnification eyepiece Γ'_{ocu} is limited by the minimum value of the focal due to aberrations, giving maximum values about 20. The objective magnification power ranges from 4 to 60.

1. ([Video](#)) Place a lens of $+50 \text{ mm}$ near the illuminated object to obtain an image at a distance of about 20cm on a translucent screen. Place a lens of $+100 \text{ mm}$ focal length on the bench and shift it up to locate the screen at its focal point. Remove the screen, adjust the eyepiece and adjust your eye distance to eyepiece ($10\text{-}15 \text{ cm}$) when looking through the microscope. Calculate the magnification of your microscope.

Chromatic aberrations are very common in this experiment. Try to observe them.

2F

SECTION F: Refractive astronomical telescope

Material

- Converging lenses with focal distances $+100$ (o $+300$) and $+50\text{mm}$ and supports.
- Optical bench.
- Translucent screen.

The telescope allows observation of distant objects in greater detail than the naked eye. The refractive astronomical telescope is composed by a long focal length converging lens (objective), and a second converging lens of shorter focal called eyepiece. The lenses are arranged so that the focal points coincide.

The objective lens creates an intermediate image in the focal plane while the eyepiece takes the same role of a magnifying glass, creating a virtual and enlarged image of the focal plane (see fig. 8):

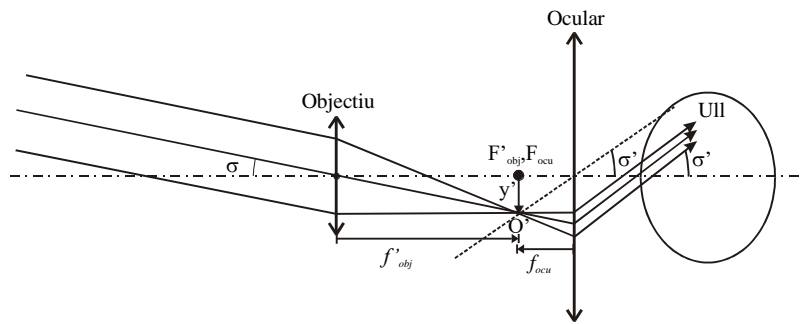


Figure 8. Image formation with a refractive astronomical telescope.

We define the magnifying power as the ratio of apparent sizes with and without telescope:

$$\Gamma' = \frac{tg \sigma'}{tg \sigma} = \frac{-y'/f'_{obj}}{y'/f'_{ocu}} = -\frac{f'_{obj}}{f'_{ocu}} \quad (12)$$

Note that the magnification is negative but it is not a drawback for sky observations.

1. (Video) We are interested in far objects, so we will not use the illuminated object. Remove it and place the +100 mm (o +300mm) focal lens on the bench. Create an image of a distant object on the translucent screen located at the focal plane. Place the eyepiece (+50 mm focal lens) taking into account that the two focal planes should coincide. Remove the translucent screen and observe through the telescope. Calculate the telescope magnification.

SECTION G: Terrestrial telescope

Material

- Lenses with focal distance +100, +200 and +50mm and supports.
- Optical bench.
- translucent screen.

The astronomical telescope is not suitable for some applications because it inverts the image. A simple solution to avoid this is by the inclusion of a third converging lens to create a double inversion. See Fig. 9.

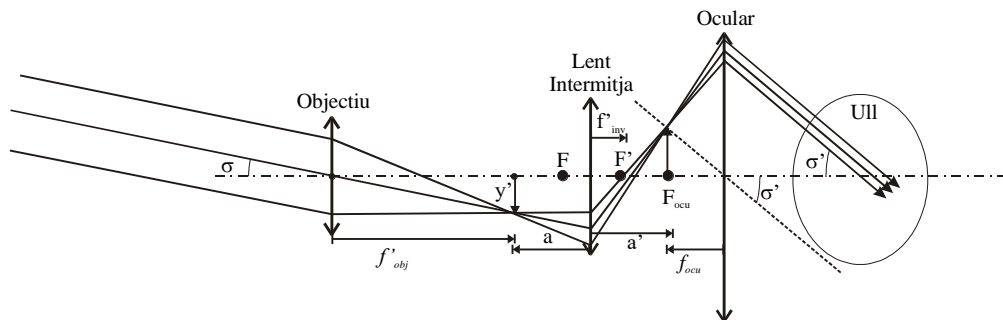


Figure 9. Image formation with a refractive terrestrial telescope.

From fig. 9, the magnification can be calculated by:

$$\Gamma' = \frac{tg \sigma'}{tg \sigma} = -\frac{y''/f'_{ocu}}{y'/f'_{obj}} = -\frac{f'_{obj}}{f'_{ocu}} \beta'_{inv} = \frac{f'_{obj}}{f'_{ocu}} \frac{a'}{|a|} \quad (13)$$

1. ([Video](#)) Create an image of a distant object on the translucent screen located at the focal plane using a lens of +100mm. Place the second ($f=+50\text{mm}$) at a distance about 100mm from the translucent screen. Remove the screen and look for the image created by this second lens using again the screen. It should be about 100mm from this lens. Place the eyepiece (+50 mm focal lens) taking into account that the two focal plane should coincide with the last image. Remove the translucent screen and observe through the telescope. Calculate the telescope magnification.

Practice 3: Light polarization. Polarization by reflection and scattering. Polarimetry. Birefringence, photoelasticity and optical activity

Introduction.

The polarization phenomena directly put in evidence the transversal character of light radiation and its vectorial nature. Remember that an electromagnetic wave is the interplay of an electric field and a magnetic field oscillating in a plane perpendicular to propagation. The oscillation direction of the associated **electric field** defines the **polarization** of the wave. The transverse plane allow different polarizations, like linear polarization (electric field oscillation always in the same direction), elliptical polarization (the electric field vector follows an elliptical trajectory when projected over a transversal plane) or circular polarization (specific case of elliptical polarization with circular trajectory). Light from some sources does not have a defined direction of polarization but rather the polarization changes **randomly** along time. The Sun or incandescent bulbs, are examples of sources of randomly **polarized or nonpolarized** waves.

3A

SECTION A: The polarizer. Malus law.

Material

- Lamp.
- Dichroic polarizers.
- Semiconductor laser.

A polarizer is an optical filter that transmits light of a specific polarization direction and blocks the perpendicular one. They can select linear polarizations or also circular polarizations. Linear polarizers can be classified as **absorptive polarizers** and **beam-splitting polarizers**.

Absorptive polarizers can be dichroic crystals that show a preferential absorption for a particular polarization but the most commonly used are Polaroid polarizing filters that acts as a wire-grid polarizer at atomic scale. They are made of polyvinyl alcohol that creates large chains that are aligned in a particular direction because of stretching during the fabrication process. They are doped with iodine, a conducting substance. The Electrons can move along the

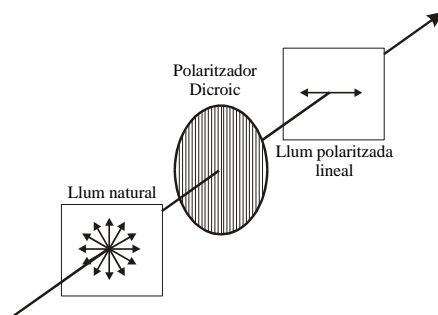


Figure 1. Operation of a dichroic polarize

polymer chains but not in transverse direction, so the incident light polarized parallel to the chains is absorbed by the sheet while light polarized perpendicularly to the chains is transmitted.

A beam of natural light passing through a first polarizer becomes linearly polarized in the transmission axis direction. Considering an ideal polarizer, half of the natural light intensity

passes through the polarizer. When light pass through a second polarizer, only the component of the electric field in the transmission axis direction is transmitted. Thus, for a given angle θ between both polarizers, the amplitude of the transmitted and linearly polarized electric field is multiplied by a factor $\cos\theta$. The transmitted light intensity, proportional to the field squared, is:

$$I(\theta) = \frac{1}{2} I_0 \cos^2 \theta \quad (1)$$

This relationship is known as Malus law.

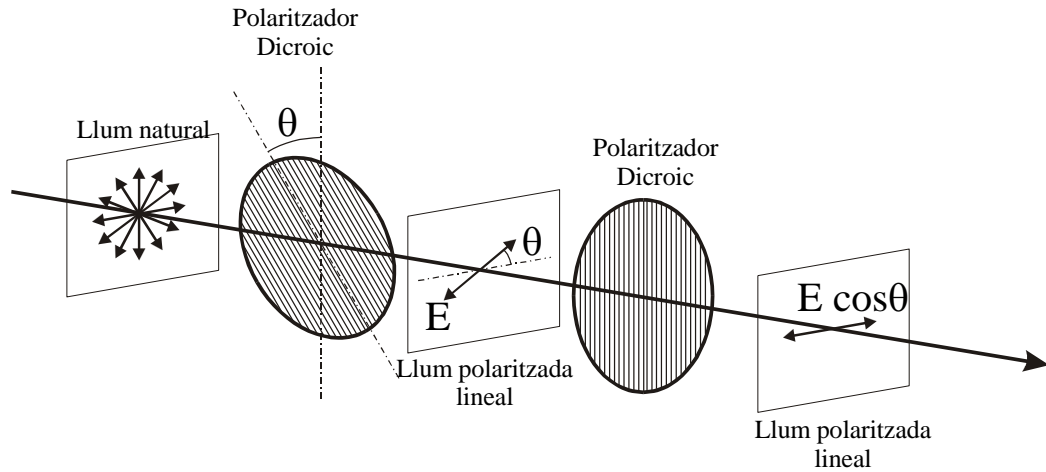
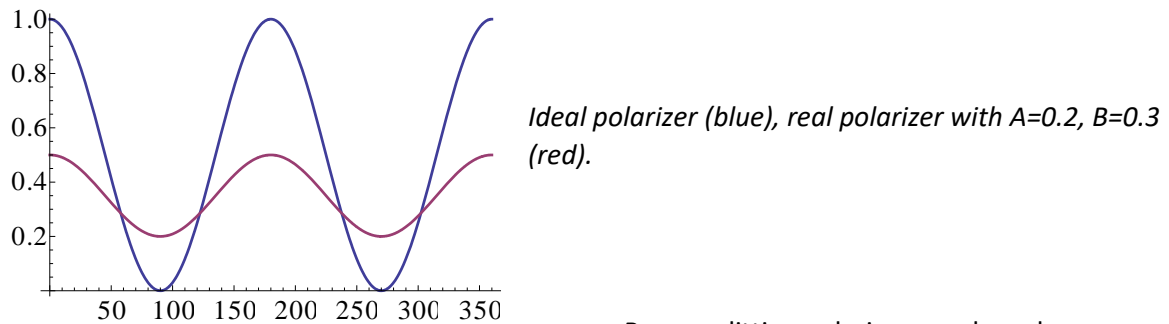


Figure 2. Muntatge experimental per a la verificació de la llei de Malus.

Polarizers used in this experiment are not ideal. Thus, the transmitted light is not completely polarized. Principal transmission factors K_1 and K_2 are defined to characterize the transmitted light. An ideal polarizer has $K_1=1$ and $K_2=0$ factors, corresponding to a total transmission for axis polarization and total extinction for the perpendicular one. For non-ideal polarizers the transmission coefficients K_1 and K_2 appear in the Malus equation that is transformed to:

$$I(\theta) = K_1 K_2 I_0 + \frac{1}{2} K_1 (K_1 - 2K_2) I_0 \cos^2 \theta = A + B \cos^2 \theta \quad (2)$$



Beam-splitting polarizers are based on birefringence. Birefringence (double refraction) can be easily seen observing an object through a calcite crystal. This crystal refractive index depends on the light polarization and propagation direction. Any light polarization can be decomposed into two transverse polarizations with different refractive index and creating two different images that can be seen through the

crystal. Turning the crystal, one image turns with it (extraordinary ray) while the second one remains stationary (ordinary ray).

1. (Video) Take one polarizer and analyse the light from the sun, bulb lamps, fluorescent lamps and laser. Deduce the polarization of these light sources.
2. (Video) (Template) Place the sensor in front of the white light source and measure electrical intensity with the amperemeter. This value is proportional to the incident light intensity I_0 . Now, introduce two polarizers between the light source and the detector. Turn one of the polarizers to find the maximum light intensity and measure again the electrical intensity (maximum microamperes). From equation (2) we observe that this value is A+B corresponding to parallel polarizers. Now, turn one of the polarizers to find a minimum electrical intensity value that corresponds to B in eq.(2), crossed polarizers. Calculate K_1 and K_2 transmission factors of the polarizer using eq.(2).

3B

SECTION B: Polarization by reflection. Brewster angle.

Material

- Semiconductor laser.
- polarizer
- photodiode
- glass plate
- Angle measuring system.

When a light beam is incident on a interface between two media with different refractive index, n_i and n_t , part of the beam intensity is reflected and part is transmitted. The fraction of reflected and transmitted light energy (or Intensity or power) depends on its polarization and on the angle of incidence and are given by Fresnel equations. R_s (T_s) is the reflectance (transmittance) for the perpendicular polarized light and R_p (T_p) is the reflectance (transmittance) for the parallel polarized light:

$$\begin{aligned}
 R_s &= \frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)} \\
 R_p &= \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \\
 T_s &= \frac{n_t \cos \theta_t}{n_i \cos \theta_i} \frac{4 \sin^2 \theta_t \cos^2 \theta_i}{\sin^2(\theta_i + \theta_t)} \\
 T_p &= \frac{n_t \cos \theta_t}{n_i \cos \theta_i} \frac{4 \sin^2 \theta_t \cos^2 \theta_i}{\sin^2(\theta_i + \theta_t) \cos^2(\theta_i - \theta_t)}
 \end{aligned} \tag{3}$$

where θ_i is the angle of incidence and θ_t is the refracted angle.

Reflectances and transmittances as a function of the incident angle are represented in figure 3 for $n_i=1,0$ (air) and $n_t=1.5$ (glass). For a particular incident angle (Brewster angle θ_B) $R_p=0$ i $T_p=1$, while $R_s \neq 0$ i $T_s \neq 1$, thus, all parallel polarized light is transmitted and the reflected beam is perpendicular polarized. The Brewster angle can be obtained imposing $R_p=0$, giving:

$$\theta_B + \theta_t = 90^\circ; \quad \tan \theta_B = \frac{n_t}{n_i} \quad (3)$$

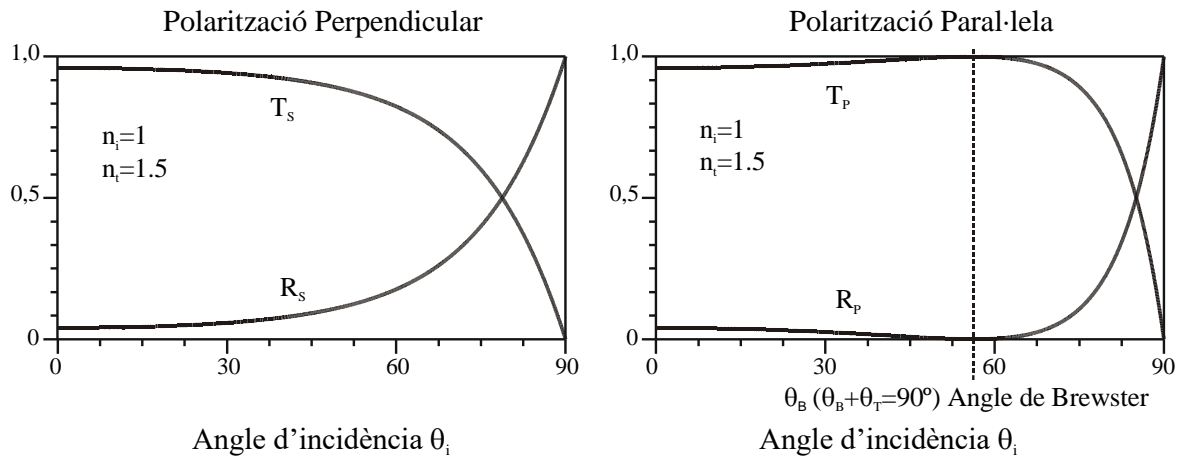


Figure 3. Reflectance and transmittance as a function of the angle of incidence with perpendicular and parallel polarization when $n_i=1, 0$ i $n_t=1,5$.

A semiconductor laser polarized at 45° and a polarizer allows us to select perpendicular or parallel polarized beams. The beam is reflected in an air-glass interface and detected by a photodiode connected to a load resistor. The obtained voltage is proportional to the light power reaching the photodiode.

1. ([Video](#)) Turn the polarizer up to obtain parallel polarized light. Measure the reflected light from normal incidence 0° to 90° in 5° intervals. Turn the polarizer up to obtain perpendicular polarized light. Measure the reflected light from normal incidence 0° to 90° in 5° intervals.
2. ([Template](#)) Plot a graphic with reflectance and transmittance ($T=1-R$) of both polarizations. You will need the incident total power from the laser for both polarizations. Remember to measure them just placing the mirror with an angle of incidence of 90° .
3. Calculate the glass refractive index from the experimentally obtained Brewster angle.
4. ([Video](#)) Take a stack of glass layers and analyze the reflected light at Brewster angle. Explain the result.

3C

SECTION C: Polarization by Rayleigh scattering.

The aim of this section is to observe light polarization through scattering by suspension particles.

Material

- Lamp.
- Transparent container.
- Ludox (or milk powder).
- Polarizers

When small particles, with sizes about light wavelength are driven by the electromagnetic wave, dipole oscillations are induced emitting secondary waves that are scattered in all directions transverse to the dipole oscillation direction. This direction is given by the incident light polarization. We speak about Rayleigh scattering when the particle size is not more than 5-10% of the light wavelength. Under these conditions light is relatively symmetrical scattered in all directions from the particle. The scattered intensity I_D can be calculated from the expression:

$$I_D = \frac{8\pi^4 \alpha^2}{\lambda^4 r^2} \sin^2 \theta I_0$$

where α is the particle polarizability, λ is the wavelength, I_0 is the incident intensity, θ is the angle between the incident and scattered wave and r is the distance from the scatter. In the high atmosphere, light is scattered by the presence of dust, water droplets and other particles. The scattered intensity is inversely proportional to the fourth power of wavelength, so small wavelengths are efficiently scattered while large wavelengths are hardly scattered. This fact explains the blue color of sky from where only scattered light arrives to us and red sunsets, when sunlight directly arrives to us crossing a long path through atmosphere.

Figure 4 indicates the propagation directions of scattered light depending on polarization direction. When both polarizations are present in incident light, scattered light in transverse directions is polarized because light is not scattered into the dipole oscillation direction. We can easily see this effect looking at blue sky in a transverse direction to the sun.

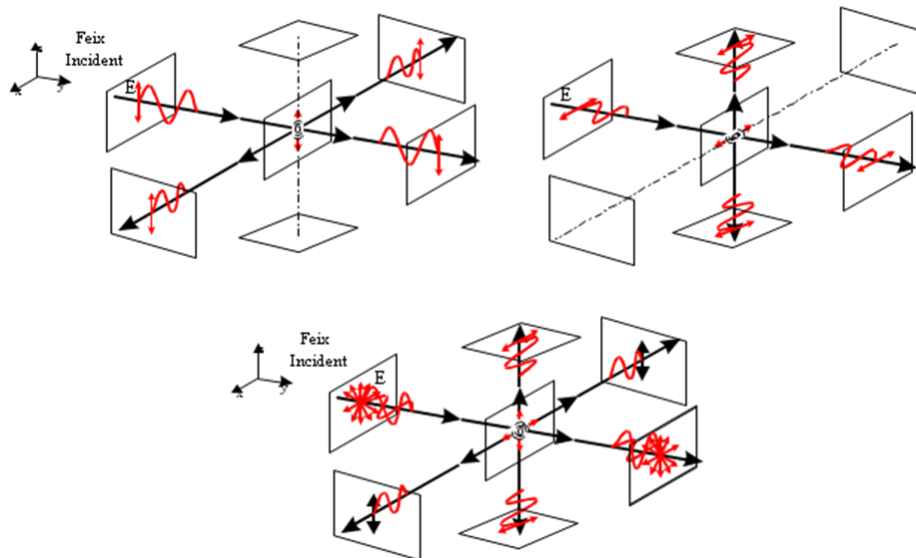


Figure 4. Diffusion of linearly polarized light and non polarized light of particle.

One of the most interesting applications of light scattering is detection and measurement of pollutants in atmosphere using a LIDAR device (Light Detection and Ranging or Laser Imaging Detection and Ranging). LIDAR emits a laser beam to atmosphere and analyze the scattered light to obtain composition and density of pollutants.

1. ([Video](#)) Look at the blue sky in normal direction to the sun through a polarizer. Compare with light from clouds and objects on earth. Note down and explain your observations.
2. ([Video](#)) Fill the container with the Ludox dissolution (Ludox flask) or with water and a bit

of milk powder. Illuminate the container with the white non-polarized light source and using a polarizer, analyze the scattered light in normal directions to the incident beam. Note down the polarization of scattered light and observe its bluish colour. Analyze polarization and colour of the transmitted light. Return the Ludox dissolution to the flask.

IV Birefringence and photoelasticity

Polarimetry

It is the measurement of polarization changes due to the interaction of light with matter to analyze this matter. It is extensively used in remote sensing, radars, astronomy, planetary science, analysis of chemical, biological substances, visualization of mechanical strains ... The light polarization changes passing through a material depends on material properties as birefringence, dichroism, optical activity, ... For instance, birefringence and optical activity are material properties extendedly used in optical microscopy to observe transparent objects like biological tissues, cells, ...

Polarimeters, polariscopes and ellipsometers are the instruments of polarimetry. They are basically a polarizer to fix the light polarization and an analyzer (another polarizer) to analyze the light that crossed the studied material.

The aim of this experiment is to observe the phenomena of birefringence in different materials.

Material

- Light source
- two polarizers
- Different plastics, adhesive tape, PMMA pieces, Calcite (Iceland spar)
- Ruler

The birefringence is the property of some materials presenting a refractive index different for each linear polarization direction. Examples include crystals like calcite (Iceland spar), plastics like polystyrene and polycarbonate that present a static stretch, many biological materials like collagen in tendons, bones, ..., and also in optical fibers due to imperfections or due to an elliptical section.

Birefringence can be easily visualized with calcite (Iceland spar). Calcite is an *uniaxial material*, there is a single direction governing the optical anisotropy called *optical axis*. Light whose polarization is *perpendicular* to the optic axis has a refractive index n_o . Light whose polarization is *in the direction of* the optic axis sees an optical index n_e .

For any ray direction there will be a polarization direction perpendicular to the optic axis, and this is called *ordinary ray* and has a refractive index n_o . The other polarization direction will be partly in the direction of the optic axis, and this is called *extraordinary ray* and has a refractive index between n_o and n_e , depending on the ray direction. The difference $\Delta n = n_e - n_o$ is called the birefringence of the material.

1. ([Video](#)) Place the calcite crystal (Iceland Spar, CaCO_3) on the table and observe the two different created images and analyze them with a polarizer. Rotate the crystal to determine which image corresponds to the ordinary ray and to the extraordinary ray. Explain your observations.

Birefringence can be detected placing the material between two crossed polarizers and analyzing the light passing through the system. Taking a light propagation direction, there

are two transverse axes in the material corresponding to high and low refractive index. A linear polarization component given by the first polarizer that matches any fast or slow axes will not change. But when light polarization has components on both axes, the progressive delay along propagation of one component introduces a phase shift that gives rise to an elliptically polarized wave. Thus, the light polarization is changing along propagation and some light that can pass through the second crossed polarizer. The output polarization depends on the traversed material thickness but also on the propagated light wavelength suffering different phase shifts. In a transverse extended material the output pattern gives information about the low and fast axes orientation in each material point.

2. ([Video](#)) Place two polarizers on the bench and different plastics, adhesive tape on a glass piece between them to observe the transmitted light when illuminating with the white light source. Turn the pieces and polarizers to observe its effect. Explain this phenomenon. Observe the colors of the different points and turn 90° one of the polarizers. How have colors changed? What colors are there compared with the initial ones?

Photoelasticity is the refractive index variation of a material due to the supported efforts. A directional strain applied on the material slightly changes its atoms or molecules positions and induces a material asymmetry and the emergence of birefringence. These strains in transparent materials can be viewed using polarimetry. Plastic copies (PMMA, ...) of the mechanical structures to study can be analyzed by polarimetry to visualize the critical points where strains are concentrated. Other materials like injected plastics directly present birefringence because of the internal strains generated when the material piece was created (Built-in stress). These strains can be easily visualized just locating the transparent piece between two polarizers, for instance a ruler, protractor,

Introducing a photoelastic material in the polariscope (a white light source, two crossed polarizers and the object to be studied between them), the output pattern shows isochromatic lines (same color) and isocline lines (zero intensity for all wavelengths, black lines). Isochromatic lines depict the same strain difference between the two stress-principal axes (directions with the maximum and minimum stress). In isoclines, the stress-principal axes are aligned with the polarizers and the incident polarization is not rotated. In general, for two crossed polarizers, the transmitted electric field amplitude is $E = E_0 \sin(2\theta) \cdot \sin(\delta/2)$, where θ is the angle between the stress-principal axes and the polarizer axes. $\delta = k \cdot l \cdot \Delta n$ is the phase shift between the ordinary and extraordinary beams that depends on the strain difference between the principal axes and the stress optical coefficient C: $\Delta n = C(\sigma_1 - \sigma_2)$. Isocline lines correspond to $\sin(2\theta) = 0$ while isochromatic lines correspond to $\sin(\delta/2) = \text{const}$.

3. ([video](#)) Illuminate with the white light source two crossed polarizers on the bench. Place plastics and PMMA pieces between the polarizers and stretch and pull them observing the transmitted light due to photoelasticity. Place the ruler, protractor and other transparent objects between the polarizers and observe the strains produced during manufacture.
4. Introduce an object to be analyzed between the two 90°-crossed polarizers, e.g. the protractor, between the polarizers. Using a lens, create an image of the object on the screen. Recognize the isocline lines (*isoclinics: curves on which the principal axes are in the same direction*) and isochromatic lines (*isochromatics: maximum constant shear stress*).

5. Fix your camera (your cell phone) on a support in front of the screen. Simultaneously rotate the two polarizers taking pictures every 5 degrees from 0° to 90°.
6. Representation of the internal strains: Superposing all pictures, draw the object and all observed isoclines (dark lines corresponding to points with stress-principal axes are parallel to polarizer axes). Draw the stress-principal axes in each point of isoclines. Following the direction of both principal axes draw the *isostatic lines* inside the object.

SECTION E: Optical activity

The aim of this experiment is to observe the phenomenon of optical activity.

Material

- White light lamp
- Two polarizers.
- Blue and red filter.
- Container.
- Dissolution flasks with sucrose concentrations: 0,100,200,300,400g/l. (Each liquid must be returned to the flask).

Optical activity is the rotation of the polarization plane of linearly polarized light travelling through certain materials. It occurs in chiral materials (no mirror symmetry). Unlike birefringence, optical activity can be observed in fluids like solutions of chiral molecules like sugars or molecules with helical structure like proteins. It can also be observed in chiral solids like quartz, stress glass for windshields or metamaterials. Another difference with birefringence is that the presence of an optically active material between crossed polarizers allows the passage of light regardless of the material orientation.

A linearly polarized wave can be understood as the sum of two circularly polarized waves (one clockwise and one anti-clockwise). Chiral materials present different refractive index for the two circular polarizations. As a linearly polarized beam passes through an optically active material, the speed difference between both circular components introduces a temporal delay, i.e. a phase shift, equivalent to a rotation of the linear polarization plane.

Many organic compounds are enantiomers, one of the two stereoisomers, designated as D and L, that are mirror images of each one. A feature of Life in Earth is the only use of D-isomers in sugars and L-isomers in amino acids. Note that polymers can only be built with one enantiomer kind and thus the synthesis of proteins or polynucleotides requires the same chirality for all monomers. Evolution chose one type. In this way, isomers can have totally different biological properties. This is observed in drugs. For instance Fluoxetine (Prozac) is an antidepressant but not active in migraine while its S-enantiomer prevents migraine. Natural drugs are usually chiral and found in nature as a single enantiomer, for instance Penicillin V. To become biologically active, chiral molecules must fit into a chiral receptor and thus only one enantiomer is active.

In chemistry and biology, the optical activity of a compound in a solution is measured as the *specific rotation*. The instrument to measure it is called polarimeter. For a compound solution with concentration c (g/ml), at a certain temperature T and for a certain light wavelength λ , the rotated angle α is: $\alpha = [\alpha]_{\lambda}^T L c$, where $L(dm)$ is the solution length and

$[\alpha]_{\lambda}^T$ is the *specific rotation* in units ($\frac{^{\circ}.ml}{dm.g}$). These measurements are usually used to quantify

isomer concentrations or the excess of one enantiomer.

1. ([Video](#)) Place in front of the light source the blue and red filter, one polarizer, the container and another polarizer. Measure the length of the tank.
You have solutions with different sucrose concentrations in flasks (water, 100g / l, 200g / l, 300g / l, 400g / l). Fill the container with each solution to measure the polarization rotation and return each solution to its flask. Looking through the system, rotate one polarizer up to cross them to obtain a minimum of transmitted light in air (upper part). Rotate the polarizer up to obtain a minimum of transmitted light through the solution (lower part). The angle difference is the rotated angle. Measure the angle of rotation for the red and blue light.
2. ([Template](#)) Represent in a graph the rotated angle as a function of concentration. Make a lineal regression to obtain the specific rotation of sucrose for red and blue light at room temperature. Compare with known values.

Pràctica 4: Interference and Diffraction

The aim of this practice is the observation of several interference and diffraction phenomena related to the wave nature of light. Students will use the most common interferometers, wave-front division and amplitude division interferometers, like Michelson-Morley, and apply them to measure micrometric lengths and light wavelengths.

Interferences

The interference phenomena observed in the superposition of two light rays, in addition to being spectacular, show how light interacts with itself and offer information about the radiation nature. These interferences can be defined as the superposition of two or more waves at the same spatial point. For instance, everybody has observed the interference phenomenon occurring in an oil stain on the road after rain or the colors in a soap bubble given by the superposition of light reflected by the two interfaces of the oil or soap layer.

Light coherence and same polarization is necessary to observe interference effects in both kind of interferometers, wave-front division and amplitude division interferometers. Coherence lengths can range from microns to km: few microns for sun light, few centimeters for conventional quasi-monochromatic sources, few meters for most common lasers and hundreds of km for single mode fiber lasers. In any case, we can minimize path differences choosing sufficiently symmetrical configurations.

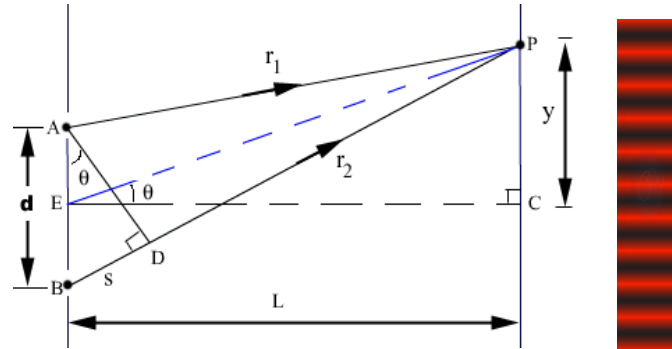
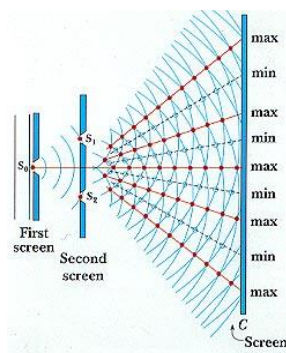
In wave-front division interferometers, the incident wave-front is spatially split in two parts that overlap on a screen. Examples of these are the Young double-slit, the Fresnel biprism and Lloyd mirrors. The two beams temporal coherence is fulfilled when the two path length difference is smaller than the coherence length of the used light. In these kind of interferometers, spatial coherence is also necessary.

In the case of amplitude division interferometers, two beams are obtained from a partially reflective surface. With a proper set of mirrors the two beams are again overlapped on the screen. In this case, spatial coherence is not needed because each point interferes with itself and extended light sources are frequently used. Some of these interferometers are Michelson, Jamin, Twyman, Mac-Zehnder and Fabry-Perot interferometers.

SECTION A: Young experiment

The Young interferometer consists of two slits, separated a distance d very small, and illuminated by a coherent light source, for example, a laser beam. Placing the screen at a

distance L much larger than d , the interference pattern is a series of equidistant bright lines. The two waves travel different paths up on the screen as they come from different slits. When the path difference is multiple of the wavelength, $\Delta r = m\lambda$, $m = 1, 2, 3, \dots$ constructive



interference occurs, while for path difference in between these values, multiples of half wavelength, $\Delta r = (m + 1/2)\lambda$, $m = 1, 2, 3, \dots$ destructive interference takes place. As we have seen in theory, for $L \gg d$ the path difference can be written as $\Delta r = d \sin \theta$, where θ is the angle from axis that fulfills: $\sin \theta \approx \tan \theta = y/L$, where y is the distance from optical axis. Then maximum intensity points are located at $m\lambda = dy/L$, $m = 1, 2, 3, \dots$ and the separation between them is $\Delta y = \lambda L/d$.

Material

- He-Ne laser with telescope to enlarge the beam section
 - Green semiconductor laser
 - Screen, ruler, graph paper.
 - Slides with double slits: slits marked as A,B,C,D:
(A: distance between slits $d=0.6\text{mm}$, slit width $a=0.12\text{mm}$)
(B: distance between slits $d=0.6\text{mm}$, slit width $a=0.24\text{mm}$)
(C: distance between slits $d=1.2\text{mm}$, slit width $a=0.24\text{mm}$)
1. (Video) Locate one of the double-slits on the support. Align the laser beam with the double-slit and screen. The screen should be far from the double-slit support. Illuminate the double-slit marked with A. Take a picture of the pattern. Obtain distance between slits Δy by measuring the length of N slits with a calliper. Repeat the same procedure for double-slits B, C and D.
 2. (Video) Determine from your measures light wavelength of the He-Ne laser.
 3. Repeat the same procedure with the green semiconductor laser. Which differences have you noticed?

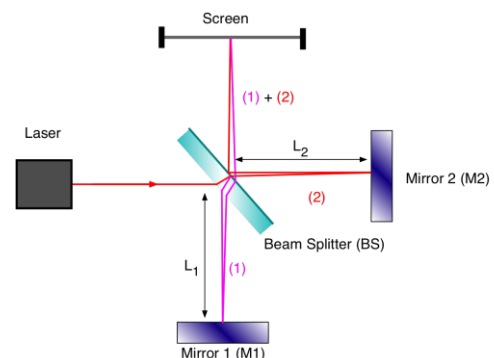
4B

SECTION B: Michelson Interferometer

Interferometers are basic optical tools used to precisely measure wavelength, distances, index of refraction, and temporal coherence of optical beams. We will use a Michelson interferometer to study the fringe patterns resulting from a parallel beam and make a precise measurement of the wavelength of the He-Ne laser.

Material

- He-Ne laser.
- Michelson interferometer



1. ([Video](#)) Switch on the laser and follow the beam path to the Michelson interferometer with a small piece of paper. Observe the pattern formed on the screen with the Haidinger rings. Tilt one of the mirrors to obtain straight interference fringes and return back to the initial position to obtain again the Haidinger rings. Explain your observations.
2. ([Video](#)) Change the length difference between the two interferometer arms turning the micrometre button to see pattern variations on the screen, rings shifting to or from the pattern centre. Explain your observations.
3. ([Video](#)) If you do not want to use the oscilloscope, vary the length difference d between the two interferometer arms about 50 or 100 μm turning the micrometre button and counting the number of fringes. Calculate the laser wavelength from your measurements.
4. ([Video](#)) Haidinger rings. Take a picture of the pattern with a dark fringe at the centre and measure the radius r_p of each ring. Plot r_p^2 as a function of the ring number p , and check the proportionality between r_p^2 and p .

SECTION C: Interferometric measurement of distances

Light interference is a simple method to measure distances and thicknesses with high precision. As an example, here we measure the thickness of thin layers and other objects.

1. ([Video](#)) Place the small cupboard with a fluorescent tube inside on the workbench. Measure the coherence length of light by increasing the distance of the two flat glass plates by different thickness films. The interference pattern disappears increasing the distance.
2. ([Video](#)) Measure the thickness of at least one plastic films and one hair using two flat glass plates. Take the two plates and shine them with the light coming from the fluorescent tubes of the small cupboard. Introduce in between the two slides a paper and find out its thickness counting the fringes and using trigonometry principles. You can measure in the same way the thickness of one hair.

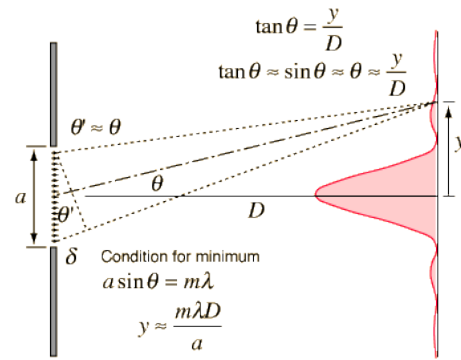
SECTION D: Diffraction

Diffraction is the phenomenon created by the simple light propagation in space. Any light distribution of diffracted and varied along propagation. Remember the principle of Huygens to explain light propagation: Each point of a wavefront acts as a new source, creating a new wavefront after a time interval. Thus, the phenomenon of diffraction can be interpreted as an interference but now we have an infinite number of points emitting waves that interfere. After a large enough distance the wavefront profile will be changed. When propagation distances are large enough we speak about Fraunhofer diffraction patterns which are not distance dependent. In this section we measure the Fraunhofer diffracted light from different apertures, slits, circular apertures or pinholes and gratings.

Suppose a slit of a certain width b illuminated by a plane wavefront and homogeneous amplitude. Each slit emits in all directions and the amplitude will be reduced with distance. Integrating electric fields emitted by each slit point, we get the total electric field and intensity at a certain distance r_0 and angle θ :

$$I = \frac{1}{2} \epsilon_0 c E^2 = \frac{\epsilon_0 c}{2} \left(\frac{E_0 b}{r_0} \right)^2 \text{sinc}^2 \beta = I_0 \text{sinc}^2 \beta$$

where $\beta = \frac{\pi b}{\lambda} \sin \theta$ and θ is the angle to axis.



We obtain intensity minima at $\sin \beta = 0$, i.e, $\sin \theta = m \lambda / b$, $m = \pm 1, \pm 2, \dots$ (but not for $m=0$).

Intensity maxima are located at $\text{tg } \beta = \beta$.

A square aperture can be thought of as an aperture width b in x and aperture b in y , thus the intensity is simply:

$$I = I_0 \text{Sinc}^2 \beta \text{Sinc}^2 \alpha \quad \text{where } \beta = kb/2 \sin \theta, \alpha = ka/2 \sin \psi$$

where θ and ψ are angles in x direction and in y direction respectively.

Similarly, for a circular aperture, the intensity presents axial symmetry and also depends on the angle from axis θ :

$$I = I_0 \left(\frac{J_1(\gamma)}{\gamma} \right)^2, \gamma = \frac{kD}{2} \sin \theta, \text{ where } D \text{ is the diameter of the aperture.}$$

In this case, the first intensity minimum appears for $D \sin \theta = 1.22 \lambda$. We can consider $\sin \theta = \theta$ for small angles.

It is worth to mention the Babinet's principle that basically stands that the Fraunhofer diffraction patterns are equal for complementary figures.

For N slits of width b and separation a between them, the diffraction pattern is given by interplay of the slit diffraction and the interference between them:

$$I = I_0 \text{Sinc}^2 \beta \frac{\sin N\alpha}{\sin \alpha}, \quad \beta = \frac{kb}{2} \sin \theta, \quad \alpha = \frac{ka}{2} \sin \theta$$

Maxima are located at $\alpha = m \pi$, i.e. when $m \lambda = a \sin \theta$, the well-known diffraction grating equation.

Material

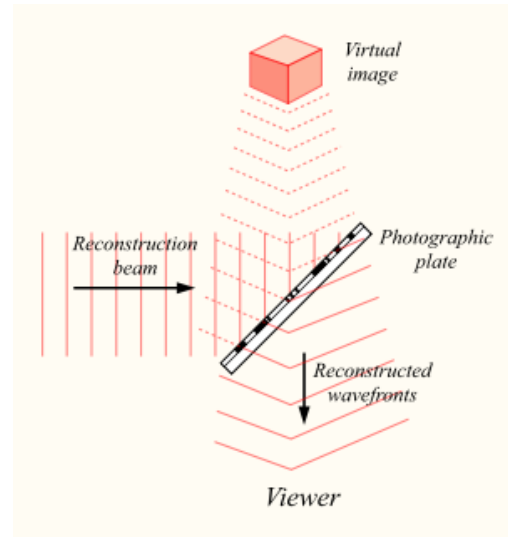
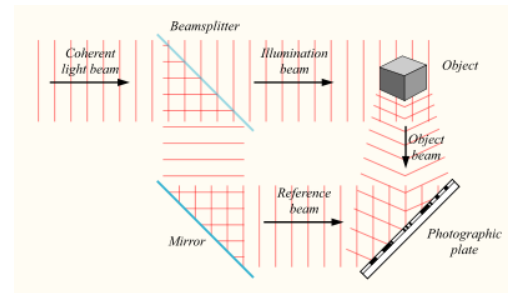
- He-Ne laser
- Telescope to open the beam

- Slits A,B,C
 - Circular apertures A,B,C, ...
 - Diffraction gratings 300 lines/mm, unknown diffraction grating
 - Ruler and graph paper
1. ([Video](#)) Locate one of the slits on the support. Align the laser beam with the slit and screen. Measure the distance between the slide and the screen. Illuminate the slit marked with A. Take a picture of the observed pattern and locate the points with maximum and minimum intensity. Measure positions of minimum and maximum intensity relative to the central point with a calliper.
 2. Repeat the same procedure for slits B,C.
 3. Calculate the three slit apertures from the diffraction pattern.
 4. Replace the slit slide by a slide with wires. Try to observe the diffraction pattern of a wire and compare it with the slit one. Explain your observations.
 5. Replace the slide and put on the support the slide with circular apertures (pinholes).
 6. Move the slide up to obtain transmitted light through the pinhole. Take a picture of the observed pattern and locate the central point and the radius with maximum and minimum intensity. Measure positions of minimum and maximum intensity relative to the central point with a calliper.
 7. Determine the pinhole radius from the observed patterns.
 8. Try to determine other larger circular apertures.
 9. Put the diffraction grating of 300 lines/mm on the support. Draw the diffraction pattern on the screen and locate the maximum intensity points and measure the distance between them. Measure the distance between grating and screen. Determine the laser wavelength of the He-Ne laser.
 10. Measure the distance between maximum points for the unknown grating and calculate its number of lines per millimetre.

SECTION E: Hologram

Holography is a technique that enables a light field, which is generally the product of a light source scattered off objects, to be recorded and later reconstructed when the original light field is no longer present. In laser holography, the hologram is recorded using a flash of laser light that illuminates a scene and then imprints on a recording medium. Part of the light beam must be shone directly onto the recording medium (the reference beam).

1. ([Video](#)) Observe the hologram.



Practice 5: Spectrometry. Wavelength measurement.

In this experiment, we will use the spectrometer to measure the wavelengths of the lines in the spectra produced by various atoms. The spectra contain bright lines at particular wavelengths, which correspond to light emitted during the transition between different energy states of the atoms. You see distinct lines because the atoms exist only in distinct, *quantized* energy states. Trying to explain the data from such experiments—the existence and pattern of sharp spectral lines—led to the development of quantum mechanics.

In the first part we take advantage of the prism dispersion to determine some wavelengths that make up the spectrum of different atoms. In the second part, a diffraction grating is used to obtain similar results. We also analyze the spectrum of other light sources.

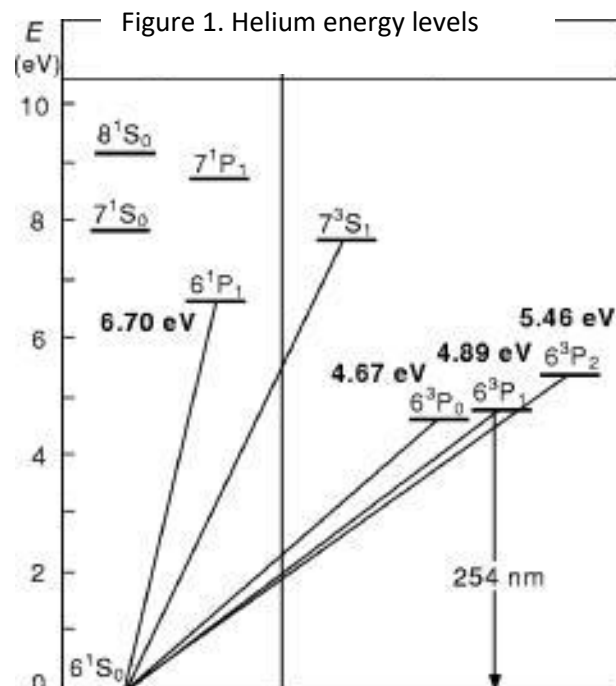
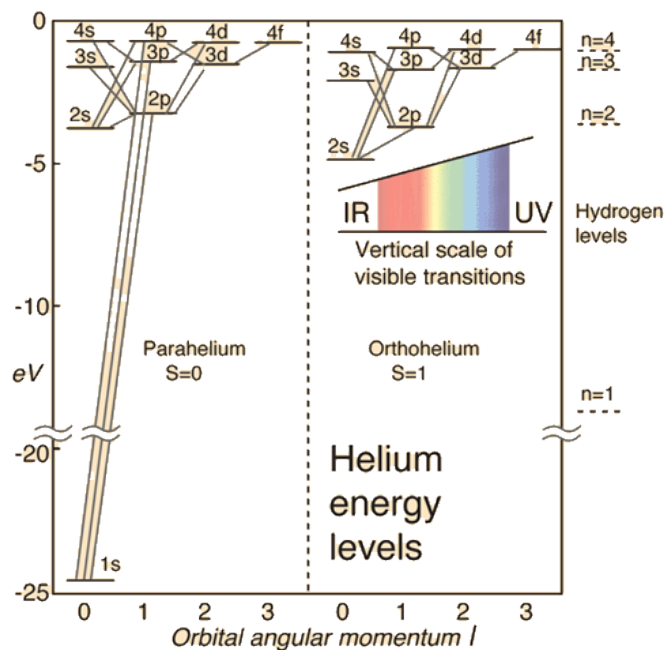


Figure 2: mercury energy levels



SECTION A: The prism spectrometer.

Material

- Spectrometer.
- Discharge lamps of different atoms
- Prism

Applying the Snell refraction law it is easy to admit the deviation of a light beam by a prism. This deviation of light rays depends on the refractive index of the prisms that is different for every wavelength. In this way, a light beam composed by a superposition of several wavelengths will be decomposed in its components. This effect is called *refractive dispersion*.

Figure 1 shows the variation of the refractive index depending on the wavelength of some optical materials. We can see that the refractive index increases when the wavelength decreases - or when the frequency increases – and it is called normal dispersion. Thus the refractive index is greater for shorter wavelengths, that is, it bends blue light more than red light. So a prism can be used to disperse white light into its component colours.

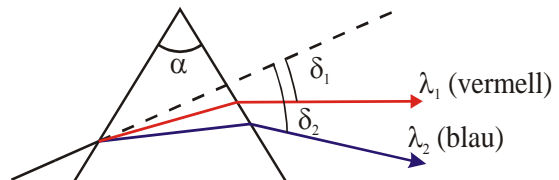
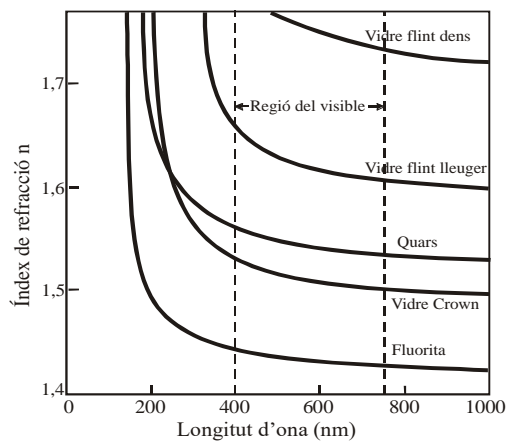


Fig.1: Dispersion through different kinds of glass. Deviation due to the prism according to wavelength.

For a given prism and a given wavelength, the deviation angle δ depends on the incident angle between the incoming ray and the normal of the surface of the prism θ_{i1} .

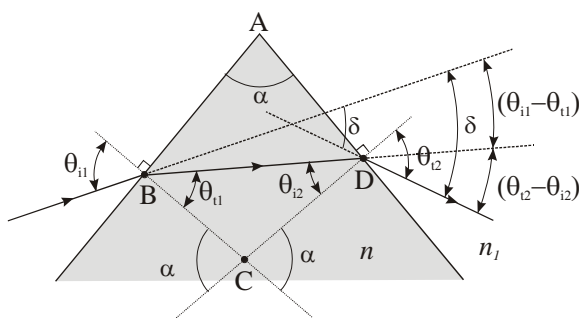
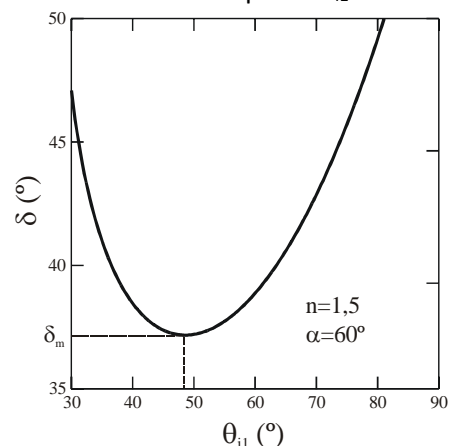


Fig.2: Relationship between the deviation angle and the incidence angle.

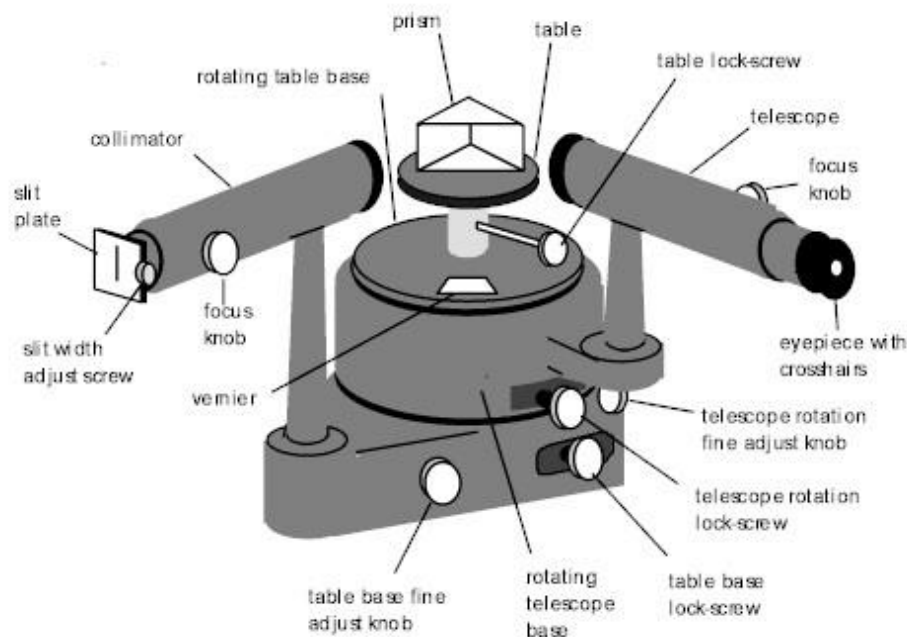


δ is minimum when the angles of the incoming and outgoing rays make equal angles with the prism surfaces. In this special symmetric case, the prism's index of refraction (n) is related to the minimum δ (δ_m) and the prism angle α by:

$$n(\lambda) = \frac{\sin \frac{1}{2}(\delta_m + \alpha)}{\sin \frac{1}{2}\alpha}$$

that allows us to measure $n(\lambda)$ just measuring the minimum deviation.

The different parts of the spectrometer are depicted in the following scheme. The important parts are the slit and width adjust screw, the collimator, the prism support, table screw, the telescope and eyepiece with crosshair, the lock screw and fine adjust knob:

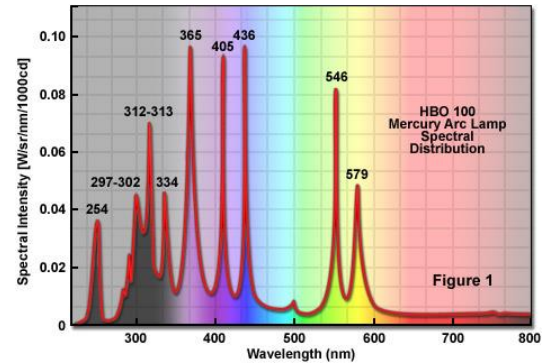


Do not put the prism on the spectrometer yet. Turn the telescope and point a far object at the other room side. You should see through the telescope clearly. Plug the Mercury lamp in the source, switch on it and place it just behind the slit and point the telescope to the slit. Align the crosshair (retícula) to the slit, it is located at the far end of the collimator. The slit should be vertical and have sharp edges. If it has not sharp edges you should adjust the collimator lens up to see a sharp image. With these conditions the light will shine the prism with parallel rays. Now, place the prism on the plate and fix it. Remember that light is bent towards the base of the prism. You can still see white light from the slit. Rotate the telescope up to see the coloured lines.

Calibration

In order to measure wavelengths we must calibrate the spectrometer with known wavelengths. We will measure the minimum angle of deviation of various wavelengths of mercury lamp to calibrate it. Wavelengths of brighter lines are given in this table (in nm):

Recognize the lines in the spectrum.



1. ([Video](#)) Observe the spectrum of mercury lamp and identify its lines with the help of table 2. Look at the lines with and without telescope. Lines seem to be inverted. Which wavelengths are more bended to the prism base, shorter or longer wavelength? Try to find an explanation.
2. Check that the position and angular distance between lines depends on the orientation of the prism. Check that there is an incident angle for which the angle of deviation of the lines is minimal. This corresponds to the minimum deviation. Is it the same for all wavelengths?
3. Select a line. Rotate the prism up to obtain the minimal deviation angle. Fix the prism at this position with the “table lock screw”. Align the crosshair to the line for measuring the deviation angle. You can lock the telescope rotation with the “lock screw” and use the “fine adjust knob” for the fine alignment. Measure the angle in the “Vernier” at this position. Now, rotate the telescope back to align the direct white light from the slit. Measure again the corresponding angle in the “Vernier”. The difference between both angles corresponds to the minimal deviation angle for this line.
4. Repeat the process for the most important visible lines: 404.66, 435.83, 546.07, 579.07.

From the measurements, we must find a direct relation between refractive index and wavelength. The refraction index as a function of wavelength has been empirically described using different formulas, Cauchy, Briot, Hartman, Here we will use the Hartmann formula that directly relates the minimal deviation with wavelength:

$$\delta(\lambda) = \delta_0 + \frac{C}{\lambda - \lambda_0} \Leftrightarrow \lambda(\delta) = \lambda_0 + \frac{C}{\delta - \delta_0} \quad (7)$$

where λ_0 , δ_0 i C are constants that can be determined from the known wavelengths and the

Groc		Verd	Verd-Blau	Blau	Violeta
579.07	567.59	546.07	491.60	435.83	407.78
	576.96			434.75	404.66
				433.92	

corresponding deviations measured with the spectrometer. The easiest way is to apply the Hartmann formula to 3 measured lines of the Hg spectrum.

5. ([Video](#)) ([Template](#)) Calculate the constants λ_0 , δ_0 and C from your measurements. You can check the calibration

with other lines of the Hg spectrum. Plot the graph $\lambda(\delta)$. Now, you have calibrated the spectroscope.

6. Replace the mercury lamp for an Helium lamp and measure the most important lines.
From the measured lines you can know which element is.

5B

SECTION B: The diffraction grating spectrometer

Material

- Spectrometer.
- Discharge lamps of different atoms
- Diffraction gratings

A diffraction grating is a periodic structure to diffract the light that can be thought as a set of parallel slits. In practical applications gratings are surface modulations. The number of slits per millimeter defines the diffraction power of the grating and can be from 50 to more than 1000. In the figure 2a is the width of each slit and $2d$ is the separation between slits.

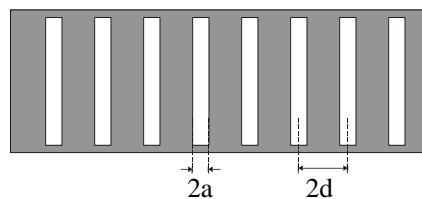


Figure 1. Diagram of a diffraction grating. The width of the slits is $2a$ and the separation between two consecutive slits is $2d$.

When a light beam reaches a diffraction grating two effects appear: every slit diffracts light and the light from all slits interfere forming the interference pattern (Fig.2). For a width in the order of λ ($\lambda \sim 2a$), each slit becomes a punctual emitter and the out coming waves interfere. The optical path difference between two parallel rays with an angle θ to axis is: $\delta = 2d \sin \theta$.

The plane wave reaching the grating must have spatial coherence to obtain interferences. It is achieved using a punctual source, the slit, in the focal point of the collimator lens.

Considering a certain wavelength, the constructive interference of light from the punctual sources is obtained when the phase difference is a multiple of the wavelength λ , i.e. when $\delta = m\lambda$ for integer m values which is called the *diffracted order*. From Figure 2, we can see that this condition for maximum interference is fulfilled when the angle θ with normal direction is: $2d \sin \theta = m\lambda$, where $2d$ is the distance between slits. This is known as the grating equation.

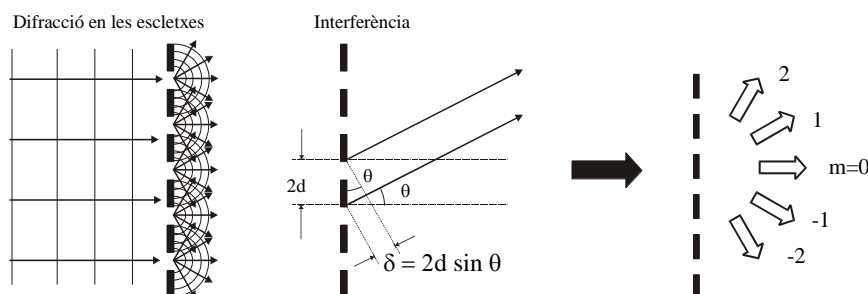
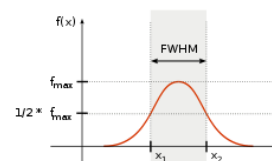
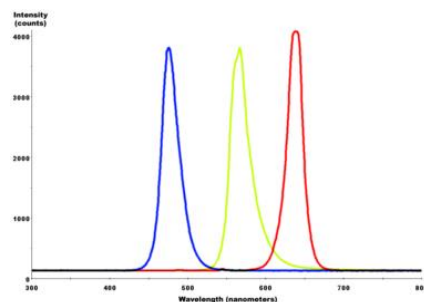


Figure 2. Diagram of the two effects involved in a diffraction grating. Firstly, the incident plane wave diffracts in the different slits, thus generating a subfront wave. Secondly, these subfront waves interfere with each other and generate the diffraction pattern.

1. ([Video](#)) Remove the prism and its support from the spectrometer and replace it by the grating support and the grating of 300 lines/mm. Do not touch the gratings with your fingers. Turn the telescope to observe the different diffracted orders for positive and negative m values. Use the mercury lamp.
2. Slightly turn the grating to see how the diffracted orders change their orientation.
3. Replace the 300 lines/mm grating for the 600 lines/mm grating. Now deviation angles are larger and only the first order is visible. Other orders do not exist because the corresponding angle would be larger than 90° and the grating condition is not fulfilled.
4. Rotate the grating up to obtain a normal light incidence. The reflected light from grating should return to the slit. You can open the slit to have a lot of light and place a white paper slit at the end of the collimator. The reflected light must return to the slit. Fix the "table lock screw". You should observe a symmetric pattern for $m=1$ and $m=-1$.
5. Turn the telescope up to see the zero order (white slit) using the lock screw and fine adjust knob and measure the angle in the "Vernier". This corresponds to zero angle $\theta=0$.
6. Measure the corresponding angle for the most important lines of 2 different discharge lamps: Hg and He.

Light from discharge lamps, the ones you have already measured, is emitted by electronic transition between energy levels giving precise photon energy and therefore a precise wavelength. Other light sources present wider bands of light emission due to a large number of electronic levels with similar energies involved in the light emission or thermal activity. Measure the spectrum of different light sources:

7. High pressure lamps, like Sodium vapor lamps, and typical Fluorescent lamps, show spectra with a continuous background and peaks related with the main radiating electronic transitions. Observe the spectrum of these lamps. Use two fluorescent tubes, one with coating and the other one without it.
8. Coloured Light-Emitting Diodes (LED) present a monochromatic light spectrum but with a large bandwidth. Measure the maximum intensity wavelength for coloured leds and their bandwidth that is specified by the FWHM (Full Width at Half Maximum), i.e. the spectral distance between the two wavelengths with an intensity value half of the maximum.



9. Analyse the wavelength spectrum of the light coming from an incandescent bulb, for example the one used in the lamp placed on the workbench.

11. Annex 2: example of questionnaire to assess these practices individually

Pregunta 1
No s'ha respost encara
Puntual sobre 1,00

Which is the alcohol concentration at minute 60 at a liquid height of 25mm?

Time evolution of the alcohol concentration

Height of the liquid (mm)	Minute 0 (%)	Minute 20 (%)	Minute 40 (%)	Minute 60 (%)
0	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
25	0.00	0.00	0.00	11.00
30	0.00	0.00	5.00	20.00
35	0.00	0.00	100.00	100.00
40	0.00	0.00	100.00	100.00

3 | Picture4 | Aproximació6 | Resultat6 | Error rates | **Evolution graph** | + | -

Trieu-ne una:

- ☐ a. 20%
- ☐ b. 11%
- ☐ c. 5%
- ☐ d. 0%

Pregunta 1
No s'ha respost encara
Puntual sobre 1,00

Is water the liquid studied with the Abbe refractometer?

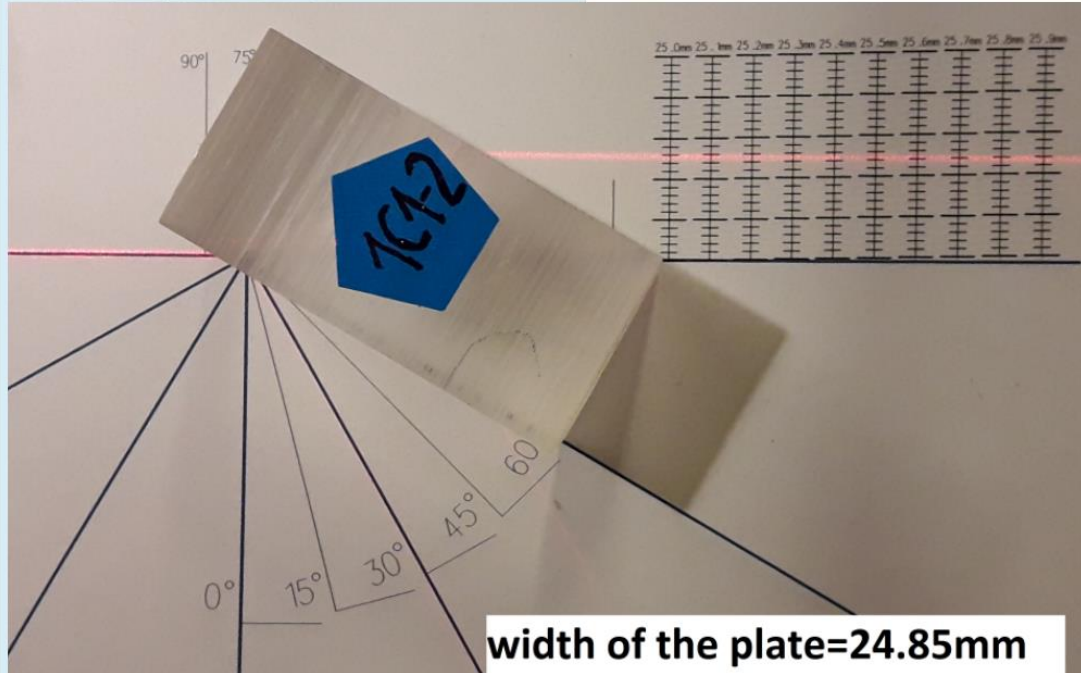
Trieu-ne una:

Respostes

- ☐ Veritader
- ☐ Fals

Pregunta 1
No s'ha respost
encara
Puntuat sobre
1.00

According to the data provided by the following picture, which is the index of refraction of the plate?



Trieu-ne una:

- ☐ a. 1.51
- ☐ b. 1.45
- ☐ c. 1.43
- ☐ d. 1.49

Pregunta 1
No s'ha respost
encara
Puntuat sobre
1.00

Is there water underneath the glass plate?



Trieu-ne una:

Respostes

- ☐ Verdader
- ☐ Fals

Pregunta 1

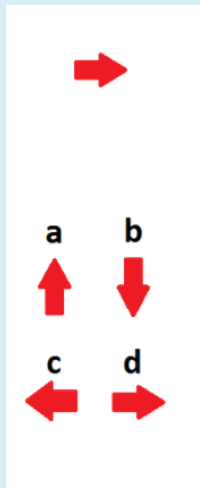
No s'ha respost

encara

Puntuat sobre

1,00

If we are looking at the first arrow with the camera obscura, which image will we get?



Trieu-ne una:

- ☐ arrow c
- ☐ arrow b
- ☐ arrow d
- ☐ arrow a

Pregunta 1

No s'ha respost

encara

Puntuat sobre

1,00

What is the focal length of the lens of this video?



Trieu-ne una:

- ☐ a. +50 mm
- ☐ b. -100 mm
- ☐ c. +200 mm
- ☐ d. +100 mm

Pregunta 1

No s'ha respost

encara

Puntuat sobre

1,00

What is it being measured?



Trieu-ne una:

- ☐ a. The resolving power of the eye.
- ☐ b. The focal length of the eye
- ☐ c. The distance between the crystalline and the retina.
- ☐ d. The near point of the eye.

Pregunta 1

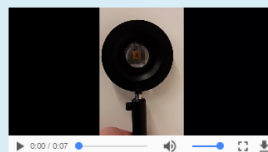
No s'ha respost

encara

Puntuat sobre

1,00

Why does the number 3 become Epsilon?



Trieu-ne una:

- ☐ a. Because the distance between your eye and the lens is greater than the focal length of the lens.
- ☐ b. Because the distance between the number 3 and the lens is greater than the focal length of the lens.
- ☐ c. Because the distance between your eye and the lens is less than the focal length of the lens.
- ☐ d. Because the distance between the number 3 and the lens is less than the focal length of the lens.

Pregunta 1
No s'ha respost
encara
Puntual sobre
1,00

Which optical instrument is showing the following video?



Treu-ne una:

- ☐ a. A refractive astronomical telescope.
- ☐ b. A simple microscope.
- ☐ c. A terrestrial telescope.
- ☐ d. A compound microscope.

Pregunta 1
No s'ha respost
encara
Puntual sobre
1,00

Which is the right distance between two lenses with focal lengths of +50 and +100 that are working as a refractive astronomical telescope?

Treu-ne una:

- ☐ a. 200 mm
- ☐ b. 50 mm
- ☐ c. 100 mm
- ☐ d. 150 mm

Pregunta 1
No s'ha respost
encara
Puntual sobre
1,00

Which is the magnification power of the telescope of this video?

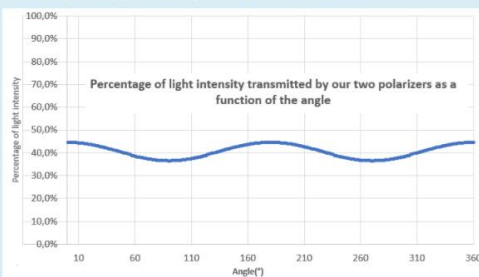


Treu-ne una:

- ☐ a. 4.44
- ☐ b. -4.44
- ☐ c. -3.6
- ☐ d. 3.6

Pregunta 1
No s'ha respost
encara
Puntual sobre
1,00

Which percentage of intensity light will pass through the two polarizers if they are rotated 50°?



Treu-ne una:

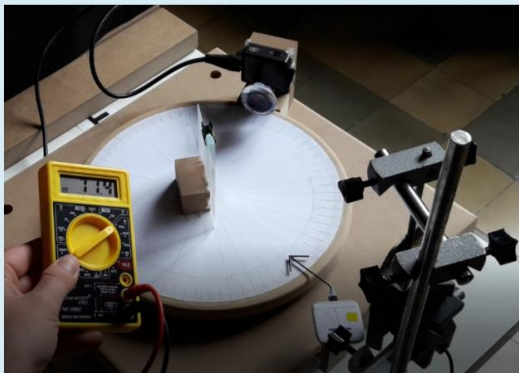
- ☐ a. 39%
- ☐ b. 44%
- ☐ c. 40%
- ☐ d. 36.7%

Pregunta 1

No s'ha respost
encara

Puntualitat sobre
1,00

If the angle of incidence is exactly the Brewster's angle, why is the ammeter measuring 77.4 microamperes?



Trieu-ne una:

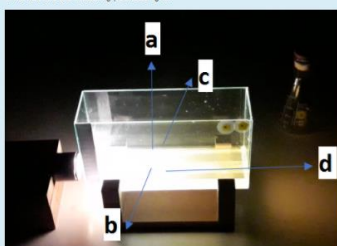
- ☐ a. Because the polarization is parallel to the surface of the glass plate.
- ☐ b. Because the multimeter is measuring voltage.
- ☐ c. Because the polarization is parallel to the surface of the wooden platform.
- ☐ d. Because the polarization is perpendicular to the surface of the wooden platform.

Pregunta 1

No s'ha respost
encara

Puntualitat sobre
1,00

Which arrows are indicating polarized light?



Trieu-ne una o més:

- ☐ c
- ☐ b
- ☐ a
- ☐ d

Pregunta 1

No s'ha respost
encara

Puntualitat sobre
1,00

At what angle of the polarizer can the ordinary ray be observed?



Trieu-ne una:

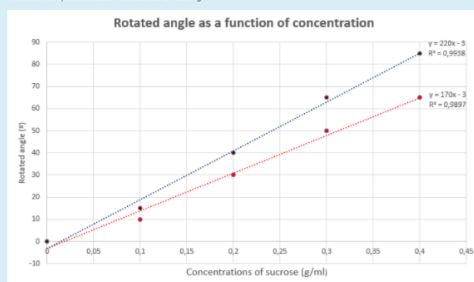
- ☐ a. 45°
- ☐ b. 60°
- ☐ c. 0°
- ☐ d. 90°

Pregunta 1

No s'ha respost
encara

Puntualitat sobre
1,00

Which is the specific rotation of sucrose for blue light?

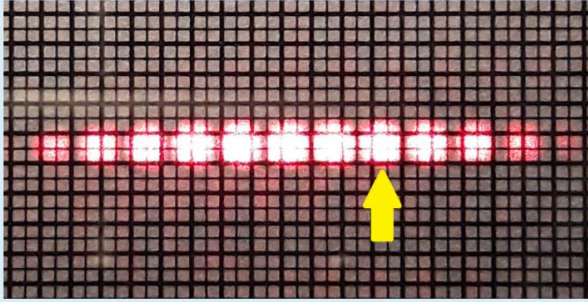


Trieu-ne una:

- ☐ a. -1.05 (°·ml)/(dm·g)
- ☐ b. 76.66 (°·ml)/(dm·g)
- ☐ c. 59.23 (°·ml)/(dm·g)
- ☐ d. 1.05 (°·ml)/(dm·g)

Pregunta 1
No s'ha respost
encara
Puntual sobre
1,00

What is the yellow arrow indicating?

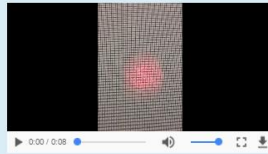


Trieu-ne una:

- ☐ a. The third constructive interference of an interference pattern.
- ☐ b. The third destructive interference of a diffraction pattern.
- ☐ c. The third constructive interference of a diffraction pattern.
- ☐ d. The third destructive interference of an interference pattern.

Pregunta 1
No s'ha respost
encara
Puntual sobre
1,00

Why are Haidinger rings appearing?

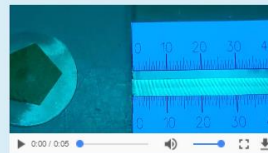


Trieu-ne una:

- ☐ a. Because the beam splitter is rotating.
- ☐ b. Because the mirror is rotating.
- ☐ c. Because the wavelength of the laser beam is changing.
- ☐ d. Because the distance between one mirror and the beam splitter is changing.

Pregunta 1
No s'ha respost
encara
Puntual sobre
1,00

How thick is the hair of the video?



Trieu-ne una:

- ☐ a. 28 μm
- ☐ b. 56 μm
- ☐ c. 28 nm
- ☐ d. 56 nm

Pregunta 1
No s'ha respost
encara
Puntual sobre
1,00

What can it be measured with the information provided by this picture if we know the position of the screen and also the wavelength of the laser beam?



Trieu-ne una:

- ☐ a. The width of a single slit.
- ☐ b. The pinhole radius.
- ☐ c. The number of lines per millimetre of a diffraction grating.
- ☐ d. The separation between two slits.

Pregunta 1
No s'ha respost
encara
Puntual sobre 1,00

What is the following picture?



Treu-ne una:
☐ a. A diffraction pattern.
☐ b. Optical activity.
☐ c. An interference pattern.
☐ d. An hologram.

Pregunta 1
No s'ha respost
encara
Puntual sobre 1,00

What is the colour of the light measured with a prism spectrometer if the Hartman's constants are $A=1.45$, $B=2.02 \cdot 10^{-8}$ and $C=1.84 \cdot 10^{-8}$ and the minimum deviation angle is 39.1° ?

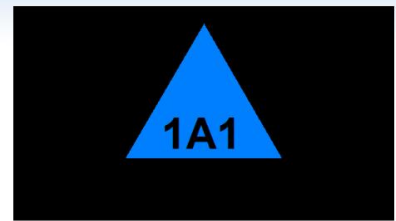
Treu-ne una:
☐ a. Green
☐ b. Yellow
☐ c. Red
☐ d. Blue

Pregunta 1
No s'ha respost
encara
Puntual sobre 1,00

What is the colour of the light measured with a spectrometer if we are using a diffraction grating with 300 lines/mm and the angle with the normal direction of light is 7.4° ?

Treu-ne una:
☐ a. Red
☐ b. Green
☐ c. Yellow
☐ d. Blue

12. Annex 3: 5 examples of video edition



00:03,03/04:52,29

1A1

PRACTICE 1

PURPOSE: MATERIAL: One vessel One screen

STEP 1: Intr...

STEP 2: pla...

STEP 3: pla...

STEP 4: pla...

STEP 5: tur...

STEP 6: adj...

STEP 7: put...

STEP 8: me...

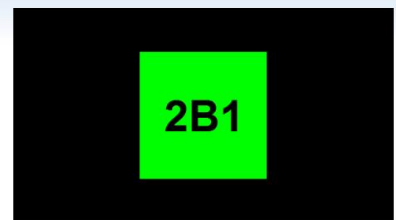
STEP 9: fill...

STEP 10: in...

The piece of

STEP 11: p...

STEP 12: re...



00:03,03/00:47,38

2B1

PRACTICE 2

PURPOSE: MATERIAL:


STEP 1: Ch... These wind...

100mm

STEP 2: rep...

STEP 3: rep...

An imag...




00:04,03/00:50,07

3C1

PRACTICE 3

PURPOSE: MATERIAL: STEP 1: dir... 90° 0°

STEP 2: rep...



00:04,03/01:46,03

◀ ▶ ⏮ ⏭ ⏪ ⏩


A PRACTICE 4
4D1
A PURPOSE:
A MATERIAL:
A STEP 1: pla...

A STEP 2: pla...
A STEP 3: pla...
A STEP 4: tur...

A STEP 5: pla...
A STEP 6...

A STEP 7: me...
A STEP 8: tur...
A STEP 9: Ide...
A STEP 10: m...

A STEP 11: ap...
A STEP 12: re...



00:03,03/04:25,83

◀ ▶ ⏮ ⏭ ⏪ ⏩

A PRACTICE 5
5A1
A PURPOSE:
A MATERIAL:
A STEP 1: tur...

A STEP 2: adj...
A STEP 3: plu...

A STEP 4: pla...
A STEP 5: pla...
A STEP 6: che...
A STEP 7: pla...

A STEP 8: co...
A STEP 7: poi...
A STEP 9: put...

A STEP 10: pu...
A STEP 11: fix...
A STEP 12: tu...

13. Annex 4: English level questionnaire

Photonics. Optics applied to engineering.

Online English level test

*Obligatorio

1. Please, write your full name *

QUESTION 1



2. In connection with this picture, which sentence is grammatically correct? Marca solo un óvalo.

☐

It's a laser beam red.

☐

Is a red laser beam.

☐

It is a red laser beam.

QUESTION 2



3. In connection with this picture, which sentence is grammatically correct? Marca solo un óvalo.

- ☐ The one that's here is the Abbe Refractometer.
- ☐ The one here is an Abbe Refractometer.
- ☐ That what is here is an Abbe Refractometer.

QUESTION 3



4. One student says that it is 13.2 mm in diameter and his teacher replies: Marca solo un óvalo.

- ☐ You have right.
- ☐ You're right.
- ☐ You're wrong.

QUESTION 4

5. Which sentence is gramatically correct? Marca solo un óvalo.

- ☐ Listen your teacher if you want to pass this subject.
- ☐ Listen to your teacher if you want to pass this subject.
- ☐ You listen to your teacher if you want to pass this subject.

QUESTION 5

6. Which question is grammatically correct? Marca solo un óvalo.

- ☐ Where is the laser beam coming of?
- ☐ From where is the laser beam coming?
- ☐ Where is the laser beam coming from?

QUESTION 6

7. Which sentence is grammatically correct? Marca solo un óvalo.

- ☐ Students normally plan to write a report later leaving the laboratory.
- ☐ Students normally think to write a report after leaving the laboratory.
- ☐ Students normally plan to write a report after leaving the laboratory.

QUESTION 7



8. One student is measuring this piece of glass and says that it is 3.05 mm thick. His classmate replies...

Marca solo un óvalo.

- ☐ I think so.
- ☐ I believe that yes.
- ☐ I think yes.

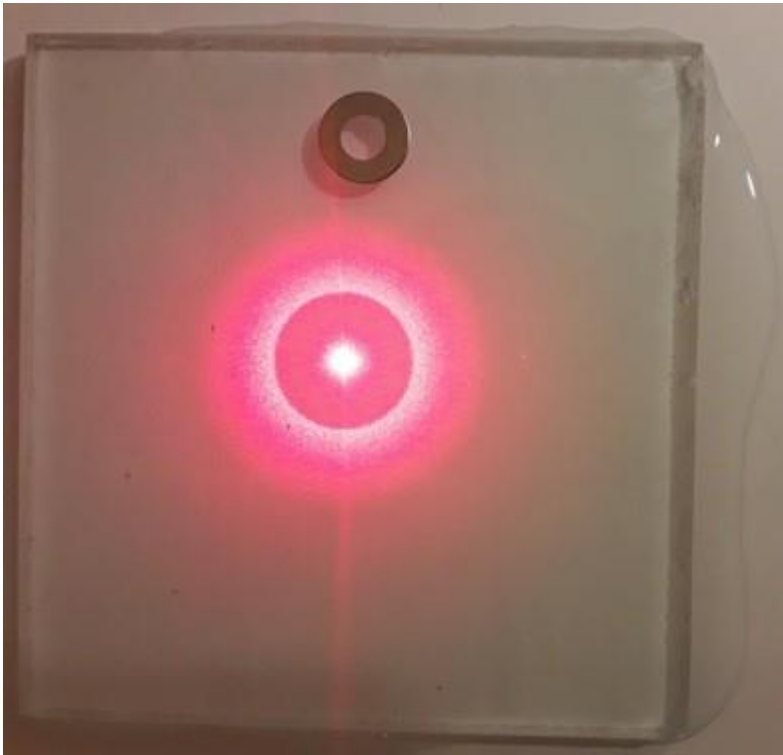
QUESTION 8

9. Which sentence is grammatically correct? Marca solo un óvalo.

- ☐ I feel badly when I find out that my results are incorrect.
- ☐ I feel me bad when I find out that my results are incorrect.
- ☐ I feel bad when I find out that my results are incorrect.

QUESTION 9

The metal piece is called washer.



10. In connection with this picture, which sentence is grammatically correct? Marca solo un óvalo.

- ☐ The washer's diameter is not so long as the red one.
- ☐ The washer's diameter is not as long like the red one.
- ☐ The washer's diameter is not as long as the red one.

QUESTION 10

11. Which sentence is grammatically correct? Marca solo un óvalo.

- ☐ Take care with the laser beam.
- ☐ Have care with the laser beam. Be
- ☐ careful with the laser beam.

QUESTION 11

12. Which sentence is grammatically correct? Marca solo un óvalo.

- ☐ Measuring the refractive index variation lasts more than an hour.
- ☐ Measuring the refractive index variation takes more than one hour.
- ☐ Students take more than one hour to measure the refractive index variation.

QUESTION 12

13. Which question is grammatically correct? Marca solo un óvalo.

- ☐ What was the teacher doing when did you speak to him?
- ☐ What was the teacher doing when you talked to him?
- ☐ What was the teacher doing when did you speak to him?

QUESTION 13

14. Which sentence is grammatically correct? Marca solo un óvalo.

- ☐ You'll never return to study photonics.
- ☐ You'll never study photonics again.
- ☐ You won't return to study photonics.

QUESTION 14

15. Which sentence is grammatically correct? Marca solo un óvalo.

- ☐ I don't know why the teacher wants me to do it.
- ☐ I don't know why does the teacher want me to do it.
- ☐ I don't know why the teacher wants that I do it.

QUESTION 15

16. Which question is grammatically correct if you are holding a pen? Marca solo un óvalo.

- ☐ Whose pen is that?
- ☐ Whose that pen is?
- ☐ Whose is this pen?

QUESTION 16

17 The lesson is over and the teacher says to his students...

Marca solo un óvalo.

- ☐ We'll see us this Tuesday coming.
- ☐ We see each other Tuesday coming.
- ☐ I'll see you this Tuesday coming.

QUESTION 17

18. Which question is grammatically correct?

Marca solo un óvalo.

- ☐ Why didn't our our teacher tell us anything?
- ☐ Why didn't our teacher tell to us anything?
- ☐ Why didn't our teacher say us anything?

QUESTION 18

19. Which question is grammatically correct?

Marca solo un óvalo.

- ☐ Who did you come with during the last practice session?
- ☐ Who did come with you during the last practice session?
- ☐ Who came with you during the last practice session?

QUESTION 19

20. Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ Let me to ask you a question.
- ☐ Let me ask you a question.
- ☐ Let me make you a question.

QUESTION 20

21. Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ There are no longer practice sessions, are there?
- ☐ There aren't practice sessions anymore, aren't there?
- ☐ There is no longer practice sessions, is there?

QUESTION 21

22 Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ The teacher's been waiting for the student to hand his report in for a week.
- ☐ The teacher is waiting for the student to hand his report in a week.
- ☐ The teacher's been a week waiting for the student to hand his report in.

QUESTION 22



23. In connection with this picture, which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ The more you move, the more blurred the picture's curve will be.
- ☐ How more you move, more blurred the picture's curve will be.
- ☐ How much more you move, how much more blurred the picture's curve will be.

QUESTION 23

24. Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ I would do it if you explain how to me.
- ☐ I would do it if you explained me how.
- ☐ I would do it if you explained to me how.

QUESTION 24

25 If 37 students have enrolled in this subject and all of them are attending the first class, the teacher can say...

Marca solo un óvalo.

- ☐ We have 38.
- ☐ We are 38.
- ☐ There are 38 of us.

QUESTION 25

26. Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ I haven't studied physics in a long time.
- ☐ It makes a long time that I don't study physics.
- ☐ It's been a long time since I don't study physics.

QUESTION 26

27. Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ I would've finished all laboratory activities in time if I would have studied the instructions.
- ☐ I'd have finished all laboratory activities in time if I have studied the instructions.
- ☐ I would have finished all laboratory activities in time if I had studied the instructions.

QUESTION 27

28. Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ You should've read the instructions before you came to the laboratory.
- ☐ You should've read the instructions before you come.
- ☐ You should've read the instructions before coming to the laboratory.

QUESTION 28

29. Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ If he won still more money, he would spend all of it.
- ☐ If he would make still more money, he'd spend it all.
- ☐ If he made even more money, he would spend all of it.

QUESTION 29

30 Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ Why should I have to spill some water on the desk during last practice session?
- ☐ Why should I have spilt some water on the desk during last practice session?
- ☐ Why I should have spilt some water on the desk during last practice session?
-

QUESTION 30

31. Which sentence is grammatically correct?

Marca solo un óvalo.

- ☐ If you don't know do it, ask your teacher about it.
 - ☐ If you don't know how to make it, ask your teacher it.
 - ☐ If you don't know how to do it, ask your teacher.
-